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THE DETERMINATION OF ATTITUDE DEVIATION LIMITS FOR TERMINATING A NON-NOMINAL TRANSLUNAR INJECTION MANEUVER

By Charles T. Hyle and Alexander H. Treadway,

Flight Analysis Branch

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MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
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THE DETERMINATION OF ATTITUDE DEVIATION LIMITS FOR TERMINATING A NON-NOMINAL TRANSLUNAR INJECTION MANEUVER

By Charles T. Hyle and Alexander H. Treadway

SUMMARY

This report contains an analysis of the translunar injection (TLI) maneuver and various factors affecting early termination requirements. A correlation between vehicle attitude and maneuver termination requirements is drawn.

It was found that, disregarding a gimbal locked ST-124 or inertial measurement unit (IMU) platforms and transposition and docking (T&D) communications and lighting constraints, total attitude limits which insure safe operations and maximum opportunity for a circumlunar alternate mission are 46° and -43.4° in pitch and 52° and -66° in yaw. Because of the possibility of inconsistent and unfamiliar IMU alignments at TLI ignition and because simplicity has always served best, a total attitude deviation of ±45° in either pitch or yaw is recommended as the TLI shut-down criteria.

INTRODUCTION

Because the TLI maneuver will occur without benefit of ground tracking, a real-time evaluation of this large thrust maneuver must be made solely by the crew using onboard displays. In reference 1, it was determined that the two independent spacecraft attitude reference frames and the associated information displayed on the two flight director attitude indicators (FDAI's) provided the most effective maneuver monitoring displays. Based on information available at that time, preliminary TLI shutdown limits of 15° attitude deviation from the expected or 10 deg/sec in rate were suggested. The rate limit is based primarily on the fact that launch vehicle malfunctions characterized by rate buildup do not recover and eventually lead to a spacecraft structural break at about 70 deg/sec.

The attitude deviation limit was based on a conservative estimate of allowable ST-124 platform drift from which a hybrid lunar alternate mission could be flown. The conservatism was introduced primarily because of the desire to keep the flight trajectory near to nominal and abort and alternate mission plans are generally defined relative to the nominal. Additional information pertinent to the final selection of attitude deviation limits has become available. The remainder of this

paper is an examination of these factors and an effort to define the most meaningful S-IVB TLI shutdown criteria.

FACTORS AFFECTING TLI ATTITUDE LIMITS

The following factors directly or indirectly affect the choice of an attitude deviation limit for shutting down the TLI maneuver.

1. Guidance and control malfunctions producing slow trajectory deviations.

2. Crew safety.

3. Alternate missions.

4. Abort planning.

5. Communication and lighting requirements during transposition and docking.

6. Platform Gimbal Lock (launch vehicle and spacecraft).

7. S-IVB Disposal.

8. Predictable variations in the nominal burn attitude history.

Guidance and Control Malfunctions (S-IVB)

Among the known S-IVB malfunctions, those which can result in slow trajectory or attitude deviations, and the associated criticalities, i.e. probability of mission loss per million flights, are

1. Loss of inertial attitude	2300
2. Loss of attitude error commands	50
3. Loss of attitude command signal	<1
4. One actuator inoperative (null)	1700
5. ST-124 platform drift	368

The first four of these malfunctions are characterized by the low rate, large attitude excursion shown in figure 1. It can be seen that the rate is less than 1 deg/sec and, therefore, probably not noticeable to the

crew, which is, of course, a major problem for the slow deviation malfunctions. Since there is a platform gimbal check (reasonableness test) in the Saturn computer, the guidance failure light is lit for a tumbling platform. Therefore, the loss of inertial attitude reference is the only failure with a spacecraft cue other than attitude deviation. From reference 2, these failures can occur in either a pitch or yaw channel, and typical deviations can reach 90° within 100 seconds of burn time. Additional studies involving these malfunctions are being made by Boeing, but are not expected to influence the S-IVB shutdown limit since attitude excursion by itself is not dangerous. Analysis of the fifth malfunction, a simulated launch vehicle platform drift, provides a way to examine some of the actual constraints. The next four sections draw largely from TLI trajectory simulations of a constant ST-124 platform drift.

Crew Safety

A typical TLI maneuver and the ignition geometry are shown in figures 2 through 7. Because the initial orbit is 100-n. mi. altitude circular, a significant error in thrust direction would be required to cause an immediate vehicle entry. The primary crew safety consideration is, therefore, to always provide a safe perigee. References 1 and 3 both show that platform drift in the negative pitch (down) direction results in immediate entry by the end of the 328-second burn. A 75-n. mi. perigee, which is the earth orbit insertion GO - NO-GO criteria, is obtained by a negative pitch rate of -0.175 deg/sec through the burn. Although positive pitch rates produce lower perigees than the negative equivalents, positive rates result in the vehicle ending the burn postpericynthion and therefore are not time critical. Using the -0.175 deg/sec rate, the maximum allowable attitude deviation that would provide a 75-n. mi. perigee altitude at the end of the burn would be (-0.175) (328) = -57°. Examining drift rates up to 1. deg/sec, however, shows that less than a 75-n. mi. perigee results if drift rates between -0.2 and -0.4 deg/sec are allowed to continue to -57°. From figure 8, the maximum deviation insuring at least a 75-n. mi. perigee is -52°. In the remote possibility that a constant drift of -0.175 deg/sec occurred, terminating the burn at a 52° attitude would mean a cutoff 42 seconds early. Even so, the trajectory must be protected against all drift rates.

Alternate Missions

Among the many possible alternate missions from a non-nominal TLI, those selected by the Apollo Alternate Mission Working group to be supported by preflight planning are described in reference 4. Those alternates involving the moon require a burn duration of approximately 290 seconds, depending on the time of the midcourse maneuver, as shown in reference 5. This burn duration normally produces an apogee altitude of about 30 000 n. mi. A CSM flyby of the moon (alternate 4) can therefore be made from a TLI which produces an apogee of about 30 000 n. mi. From

figure 9 the maximum allowable platform drift rates which can result in a 30 000-n. mi. apogee altitude are -0.18 deg/sec and +0.175 deg/sec in pitch and +0.125 deg/sec in yaw. Respective deviations by the end of TLI are -59°, +57° and 41°. Because these limits provide only a 30 000-n. mi. apogee altitude, a closer examination is necessary to insure that the direction of the deviated TLI is within SPS correction capability. In the previous section the maximum allowable negative pitch limit was -52°. Although this limit is too restrictive for the -0.175 deg/sec case, the flyby could still be accomplished by making the hybrid midcourse correction at about 3 hours past TLI instead of 4 hours. Alternate lunar missions being planned include:

Designation	Description
4	CSM circumlunar
5A	Hybrid circumlunar with the LM (2000 fps ΔV is saved for abort)
5B	CSM lunar orbit
6	Lunar orbit with LM; no rendezvous
7	Return to nominal

For each of these alternates, a contingency ΔV has been subtracted from the available, and the result, as shown in table I, is an approximate ΔV for use as a "midcourse correction" from a deviating TLI. Using the midcourse ΔV (ΔV_{MCC}) for each alternate with figure 10, the maximum allowable drift rate in both positive and negative pitch and yaw can be established as in table II. For constant drifts through TLI, the resulting deviations are shown in table III. Figure 10 is only approximate for alternates 5B, 6, and 7 but does serve to demonstrate the wide choice of acceptable deviations according to objectives. It was assumed the midcourse would be made at TLI plus 3 hours and the total flight time would not exceed 160 hours. Table IV shows the variation in pericynthion. Also a ΔV_{MCC} of 7000 fps was used for alternate 4, and 1000 fps was saved for a possible delay in making the midcourse. Assuming that limits should be selected for only the widest acceptable situation, the alternate 4 deviations give -54° and +61° in pitch and -66° and 52° in yaw. Again the -52° limit for negative pitch takes precedence. It is noted the attitude deviation presented in table III could vary slightly depending on the month of launch. (The February 2, 1968 first opportunity injection from a 72° launch azimuth is the nominal reference for this report.)

Abort Planning

Through several months of in-house MPAD and TRW discussions, preliminary abort procedures were defined and eventually agreed to in Apollo Abort Working Group meetings. One of these planned abort techniques consists of shutting down the TLI if the crew should need to enter immediately. Although such a time-critical failure has not been identified, the technique, referred to as the fixed attitude abort, is provided for safety. Reference 6 contains most of the associated details. If such an abort were required following a slow drift of the S-IVB, normal dispersions in performing the abort maneuver result in an entry which is no longer in the V-versus-γ entry interface corridor. Normally this would be handled by an entry midcourse maneuver; however, a minimum S-IVB burn is required in order to have time to perform such a midcourse. The maximum allowable rates discussed so far are ± 0.2 deg/sec. These rates and the minimum S-IVB burn time provides the maximum deviation which insures the fixed attitude abort maneuver does not result in an entry out of the corridor without allowing enough time to correct with the midcourse. Reference 7 resulted in a study of the S-IVB burn time required to generate the boundary shown in figure 11. This pitch attitude deviation is (0.2 deg/sec) (230 sec) = 46° and (-0.2°/sec) (217 sec) = -43.4°. For the lunar mission, the fixed attitude abort may produce a land landing; however, for the E mission the delay time to SPS ignition is established to insure water landing. Allowing significant attitude deviations may also result in land landings for the E mission.

Communications and Lighting Constraints

The impact of deviating trajectories on communication and lighting constraints can be examined with a typical attitude profile providing optimum S-IVB high gain tracking and sunlight angles as described in reference 8. At-TLI-plus 15-minutes, the S-IVB would pitch to a preflight loaded attitude, which it would hold throughout T&D-TLI-plus-2-hours. Since this attitude is optimized to give favorable tracking for two hours, a small change in initial attitude, as caused by platform drift, could easily cause loss of required telemetry by the ground. Even though the crew could hold proper attitude from the spacecraft, this capability is lost when they separate for T&D. Although it is planned to do T&D for all the alternate missions (reference 9), this objective could be dropped for alternate 4.

Alternate 5A, however requires T&D and, as seen from table III, could mean a -33° or a 41° error in S-IVB communication attitude. This is the initial error and does not include additional error through T&D. Possible lighting effects which depend on the intended lunar landing sight and a communications attitude are depicted in figure 12.

Because the optimum communication attitude and lighting conditions vary, maximum attitude deviation limit is not easily determined; however, it most likely would have to be fairly small - probably less than 30°. Only partial tracking would be available then. Possibly the crew could remain on the S-IVB and control the attitude until the ground established that it was safe for T&D. The crew could then execute a manual T&D as soon as possible. Delay past TLI-plus-3-hours would increase in the ΔV_{MCC} required.

Platform Gimbal Lock (LV and SC)

Launch vehicle.- The gimbal lock limit on the ST-124 platform in the Saturn is 60° in the yaw plane. Prior to reaching this limit onboard logic limits the maximum attitude error command to 45°. Since most of the malfunctions producing the slow deviations are attitude error signal problems of some type, yawing beyond these limits still is not likely to change response drastically. Therefore the burn could be continued to the yaw plane alternate mission limits or until a possible spacecraft gimbal lock limit.

Spacecraft.- The three gimbal platforms (IMU) in the spacecraft presently cease to provide valid attitude information when yawed past 85°. Many measures have been taken to avoid such an occurrence. However, recent developments during meetings of the Apollo Data Priority Midcourse Techniques Group have eliminated the requirement for the entire primary guidance and navigation control subsystem (PGNCS) for some lunar missions, which of course negates the requirement for the IMU. It is felt that the stabilization and control subsystem (SCS) provides an adequate backup system. With this in mind there does not appear to be much justification for TLI shutdown to prevent IMU gimbal lock.

Since most of the malfunctions previously described can produce this problem and if for some reason gimbal lock must be avoided, time (attitude deviation) would have to be allowed for the spacecraft to separate and damp rates.

If 3 seconds are provided from shutdown to SPS ignition, only 55° yaw attitude excursion from lift-off orientation could be allowed, considering a 10 deg/sec rate limit, to avoid IMU gimbal lock. For a typical TLI plane change, this means a yaw attitude deviation of 42° (i.e., 55° - 13°). If we had committed to TLI with no PGNCS, the SCS electronic gimbal lock at 75° reduces the attitude deviation limit to 32°.

In summary to avoid IMU gimbal lock, an attitude deviation limit of about 42° is required, however, since the crew has three hours to midcourse time they could probably realign. Therefore, the gimbal lock avoidance is not a mandatory requirement for TLI shutdown.

S-IVB Disposal

It is noted that even though positive pitch rates during TLI result in the spacecraft being post perigee after TLI, a low perigee such as allowed for alternate 4 may also provide S-IVB disposal problems. Reducing the allowable positive pitch limit to less than 60° improves chances of a gradually decaying orbit for the S-IVB and may therefore prevent what would probably be a land impact.

Predictable Attitude Variations

Three things should be noted under this topic. The first item concerns the propellant utilization system which can, as observed on the AS-501 mission, change the expected attitude history of the launch vehicle considerably and still be on a good trajectory. The amount of excursion depends primarily on the amount of liquid hydrogen available. It is felt that this item should not influence limit setting because the attitude excursion is predictable preflight, as is the time the propulsion unit (PU) system is active. Also, since the AS-501 mission was a special attitude case and since the remaining S-IVB second burns, such as TLI will occur primarily near the horizontal, attitude excursions are expected to be significantly less. These predicted profiles are usually available in Marshall Space Flight Center documents such as reference 2.

The second item in this category concerns the way the S-IVB is currently programed to go to the expected ignition attitude. It always moves to a prestored gimbal position regardless of the parking orbit dispersions. This could mean it is aligned initially as though it were in a 100-n. mi. circular orbit. After ignition and active guidance begins, compensation would be made for the attitude. Even if the parking orbit was a 100-by 1000-n. mi. altitude one, the maximum deviation would only be about 6°, and, of course, the crew would expect this.

The third item concerns other parking orbit dispersions and the effects on burn attitude. Reference 10 contains attitude histories through the E and G mission second S-IVB burns. Dispersions include state vector, ignition time and thrust errors. The resulting attitude deviations are generally less than 5° and are therefore excluded as shutdown limits.

General Information

Several changes from the monitoring section of reference 1 are described here for completeness. The DSKY parameters now available are from the maneuver monitor program 47. In addition to ΔV_x, ΔV_y, and ΔV_z - the components of velocity accumulated as measured in spacecraft control axes - inertial velocity (V_I), altitude rate ($\dot{h}$) and altitude (h) are

available. Also routine 30 will enable the crew to monitor apogee altitude (h_a), perigee altitude (h_p), and time to perigee (t_p).

The deletion of program 15 eliminated a possible means of TLI control by the CMC and also removed a possible cue for cutoff as well as attitude error displays. Although the ΔV meter can provide a backup cue for cutoff, chances of providing a meaningful cutoff backup are small since only a few seconds remain until fuel depletion.

Another significant change requires that the spacecraft inertial reference systems will be aligned to the launch pad alignment, as is the S-IVB, for RTCC and ground control convenience. This means that the initial pitch attitude of the FDAI displays can be anything between 0° and 360° depending on injection opportunity.

Summary Remarks

An important ground rule being used by the Midcourse Techniques Group to establish a NO-GO for TLI relies on detecting Saturn or PGNS errors which are larger than certain specification values. Acceptance of large TLI attitude deviation limits is somewhat contradictory to this ground rule.

Perhaps the most significant item not yet discussed is simplicity. Without regard to simplicity, the widest acceptable limits for shutting down TLI are + 46° and -43.4° in pitch and + 52° and -66° in yaw. Recalling that attitude deviation is the difference in spacecraft FDAI attitude and the nominal attitude at a given burn time, plus the fact that deviation can occur in a combination pitch and yaw direction, it is felt that one limit should be used. It is therefore suggested that for simplicity the translunar injection maneuvers be terminated on a total attitude deviation limit of 45° in either pitch or yaw. The primary constraint not met by the above limit is the communications and lighting requirements. If an alternative such as previously described is not acceptable, smaller limits must be imposed and even then the communication and lighting requirements may not be achieved. It is noted that during the last few seconds of TLI, as in the launch phase, action by the crew on an attitude deviation limit may be dropped because slow deviations cannot significantly jeopardize the trajectory.

It is emphasized that the probability of a slow deviation malfunction is extremely unlikely; however, since they can occur as well as cause serious problems, limits are required.

Description of Figures

Typical histories of previously discussed parameters are included in the figures. In addition to the figures used to derive limiting conditions, DSKY quantities, attitude histories, and geometry variations are provided for both pitch and yaw platform drifts. It is noted that the figures involving alternate mission midcourse ΔV are conic solutions and as a result are approximate.

CONCLUSIONS

Disregarding a gimbal locked ST-124 or IMU platform and T&D communications and lighting constraints, total attitude limits which insure safe operations and maximum opportunity for a circumlunar alternate mission are $+46°$ and $-43.4°$ in pitch and $+52°$ and $-66°$ in yaw. Because of possible inconsistent and unfamiliar IMU alignments at TLI ignition and because simplicity has always served best, a total attitude deviation of $\pm 45°$ in either pitch or yaw is recommended as TLI shutdown criteria.

TABLE I.- LUNAR ALTERNATE MISSIONS AND ALLOWABLE ΔV

Alternate mission	Designation	Total ΔV, fps	Allowable ΔV for alternate mission, fps
CSM circumlunar	4	10 000	7000
CSM/LM circumlunar	5A	5 000	3000
CSM lunar orbit	5B	10 000	4000
CSM/LM lunar orbit - no rendezvous	6	5 000	~1000
Return to nominal	7	5 000	~150

TABLE II. - ALLOWABLE ATTITUDE RATES FOR LUNAR ALTERNATE MISSIONS

Alternate mission designations	ΔV_{MCC}, fps	Negative pitch drift rate deg/sec	Positive pitch drift rate, deg/sec	Negative yaw drift rate, deg/sec	Positive yaw drift rate, deg/sec
4	7000	-.1645	.1855	-.20	.1655
5A	3000	-.1000	.1260	-.1580	.0805
5B	4000	-.1195	.1430	-.1727	.1020
6	~1000	-.0475	.0700	-.1200	.0300
7	~ 150	-.0050	.0100	-.0900	.0010

TABLE III. - ALLOWABLE ATTITUDE DEVIATIONS FOR LUNAR ALTERNATE MISSIONS

Alternate mission designation	ΔV_{MCC}, fps	Negative pitch, deg	Positive pitch, deg	Negative yaw, deg	Positive yaw, deg
4	7000	-54.0	60.9	-65.8	52.5
5A	3000	-32.8	41.3	-51.8	26.4
5B	4000	-39.2	46.9	-56.7	34.4
6	~1000	-15.6	22.9	-39.4	9.8
7	~ 150	-1.6	3.2	-29.5	.3

TABLE IV.- APPROXIMATE PERICYNTHION ALTITUDE FOLLOWING AN ALTERNATE MISSION MIDCOURSE

Pitch drift rate, deg/sec	Pericynthion altitude, n. mi.			
	TLI burn time, sec			
	300	310	320.04	328.4
-.1	89.46	135.53	84.07	98.47
-.05	80.93	130.77	209.11	59.98
0	150.37	59.98	73.94	164.12
.05	195.68	70.09	71.99	66.42
.1	65.26	63.54	60.03	68.06
Yaw drift rate, deg/sec	TLI burn time, sec			
	300	310	320.04	328.4
-.1	96.34	93.60	69.81	79.23
-.05	97.92	209.98	69.74	135.95
0	150.37	59.98	73.94	164.12
.05	93.64	145.27	63.74	77.11
.1	93.21	161.26	95.64	239.17

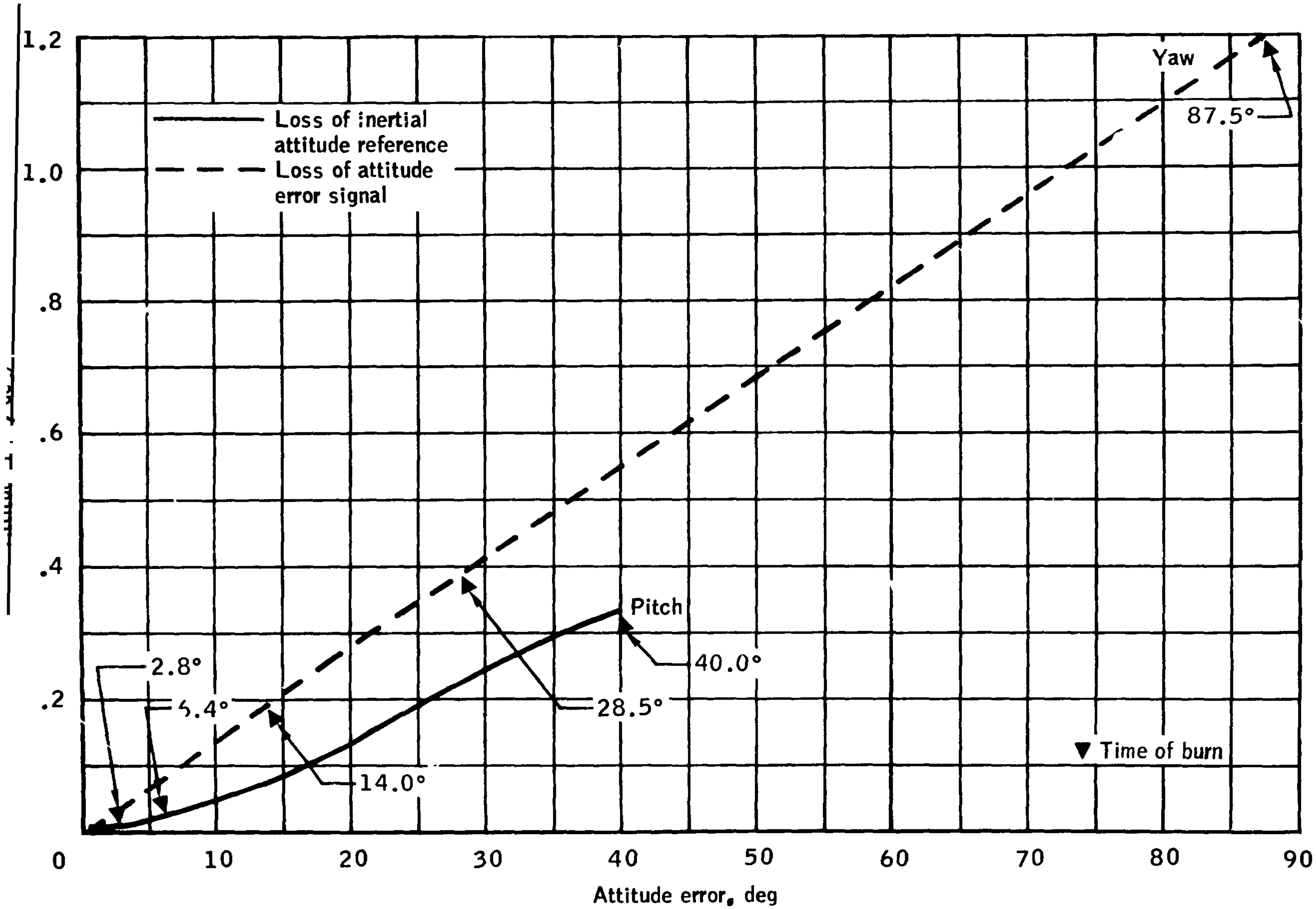
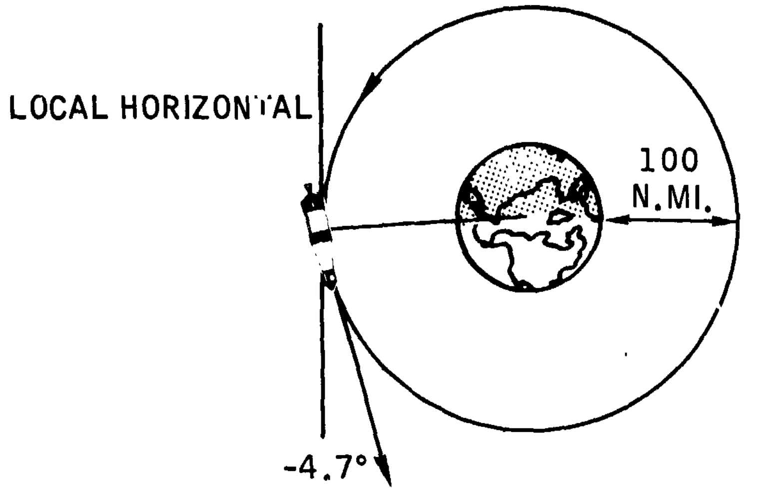
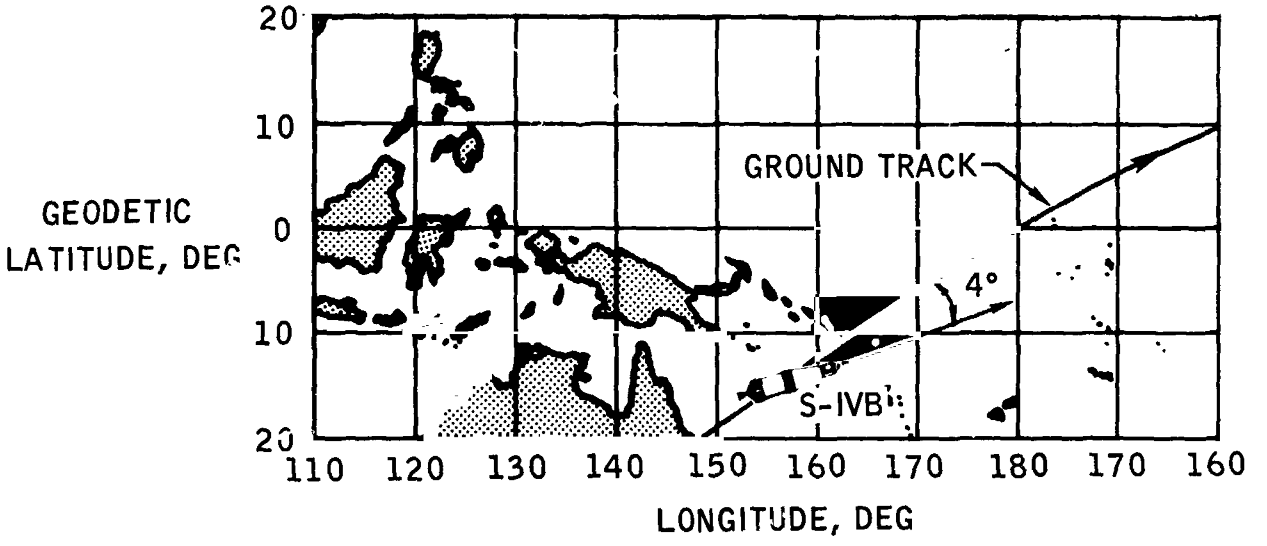


Figure 1.- Typical attitude excursions during translunar injection due to slow deviation S-IVB malfunctions.



PITCH WITH RESPECT TO LOCAL HORIZONTAL



YAW, LOCAL HORIZONTAL SYSTEM

DATA REFERENCE:
MSC INTERNAL NOTE NO. 66-FM-70

Figure 2. -Launch vehicle attitude at TLI ignition.

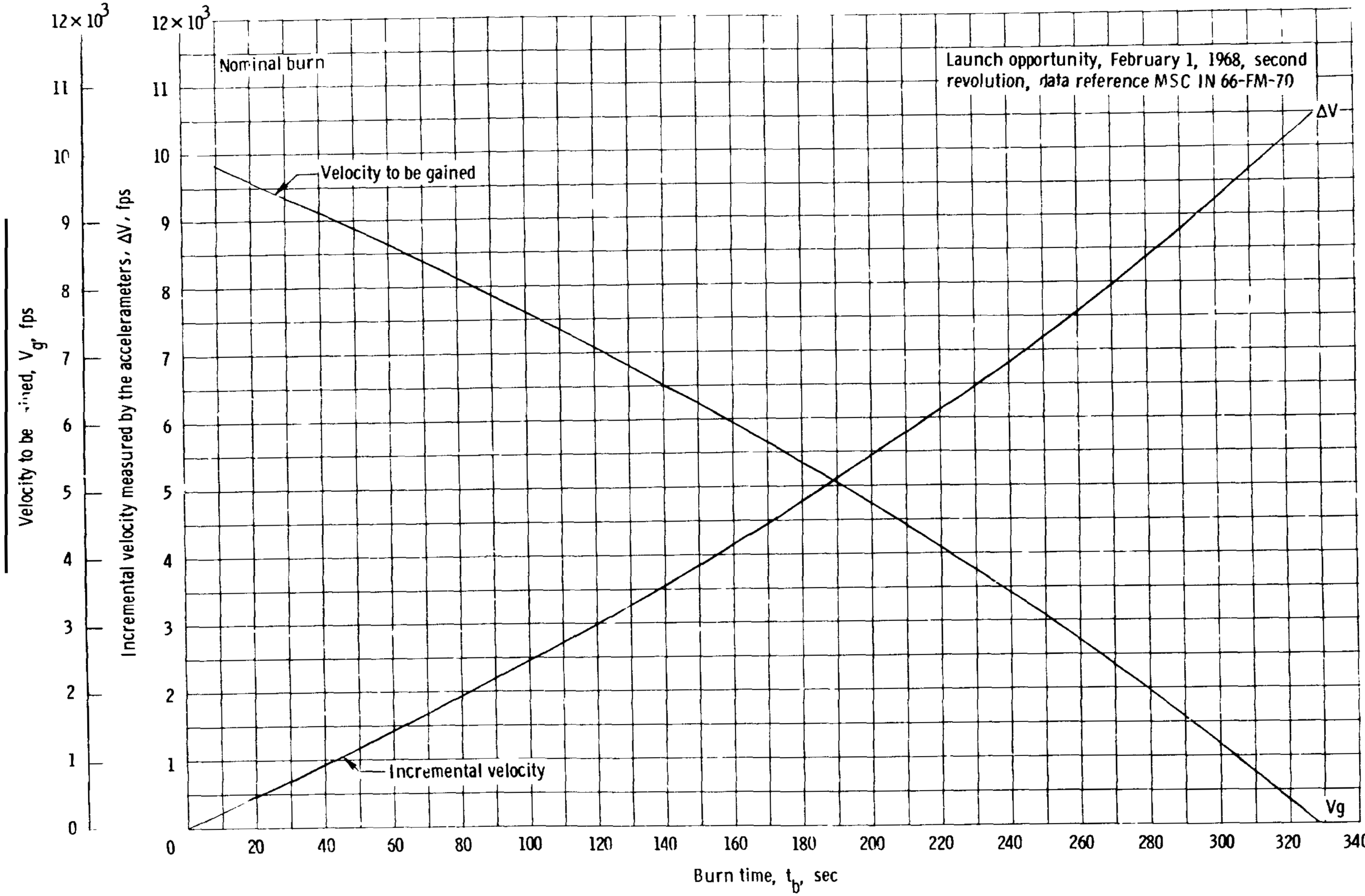


Figure 3. - Velocity change through the translunar injection burn.

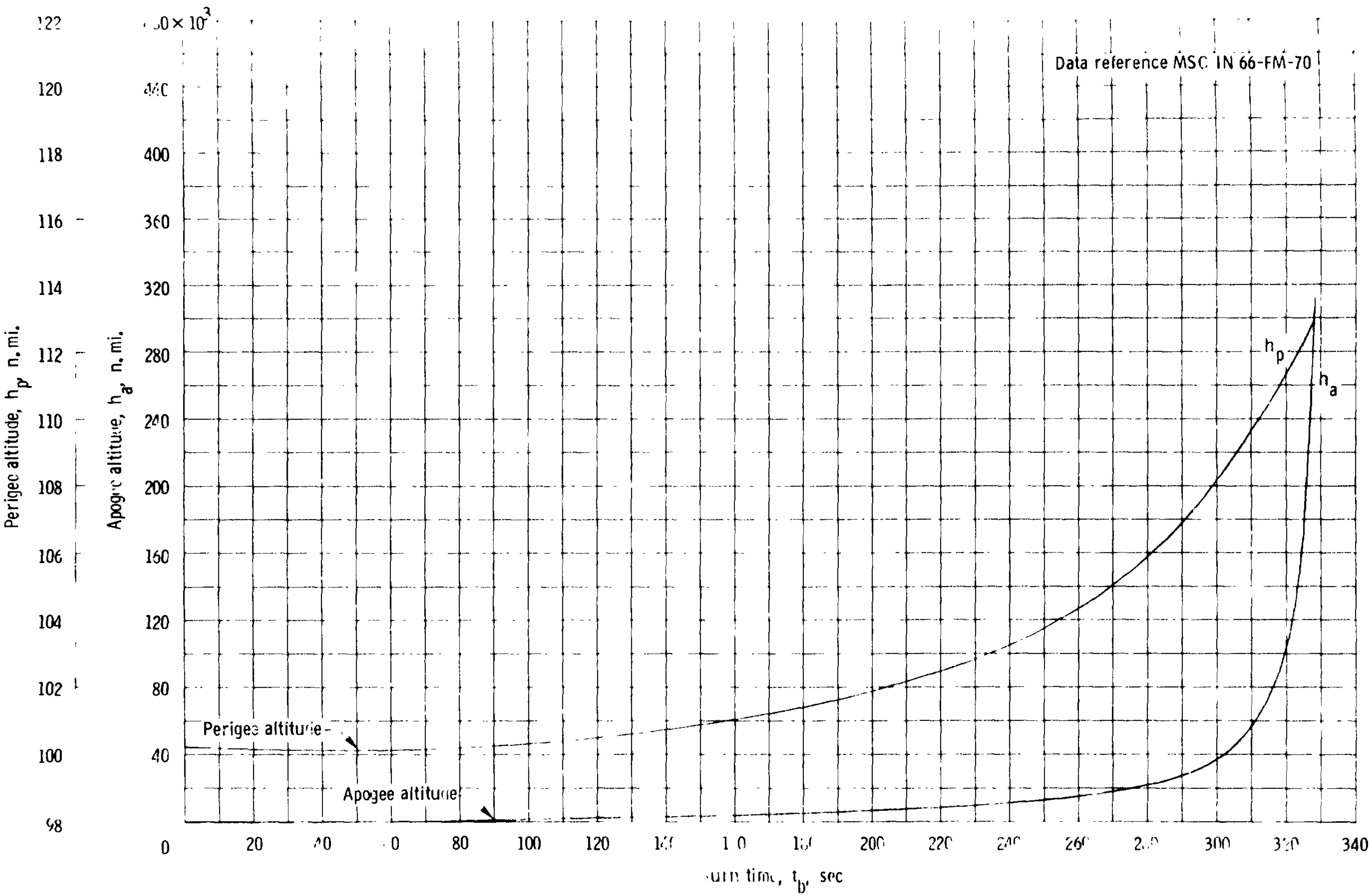


Figure 4. - Apogee altitude and perigee altitude through the translunar injection burn.

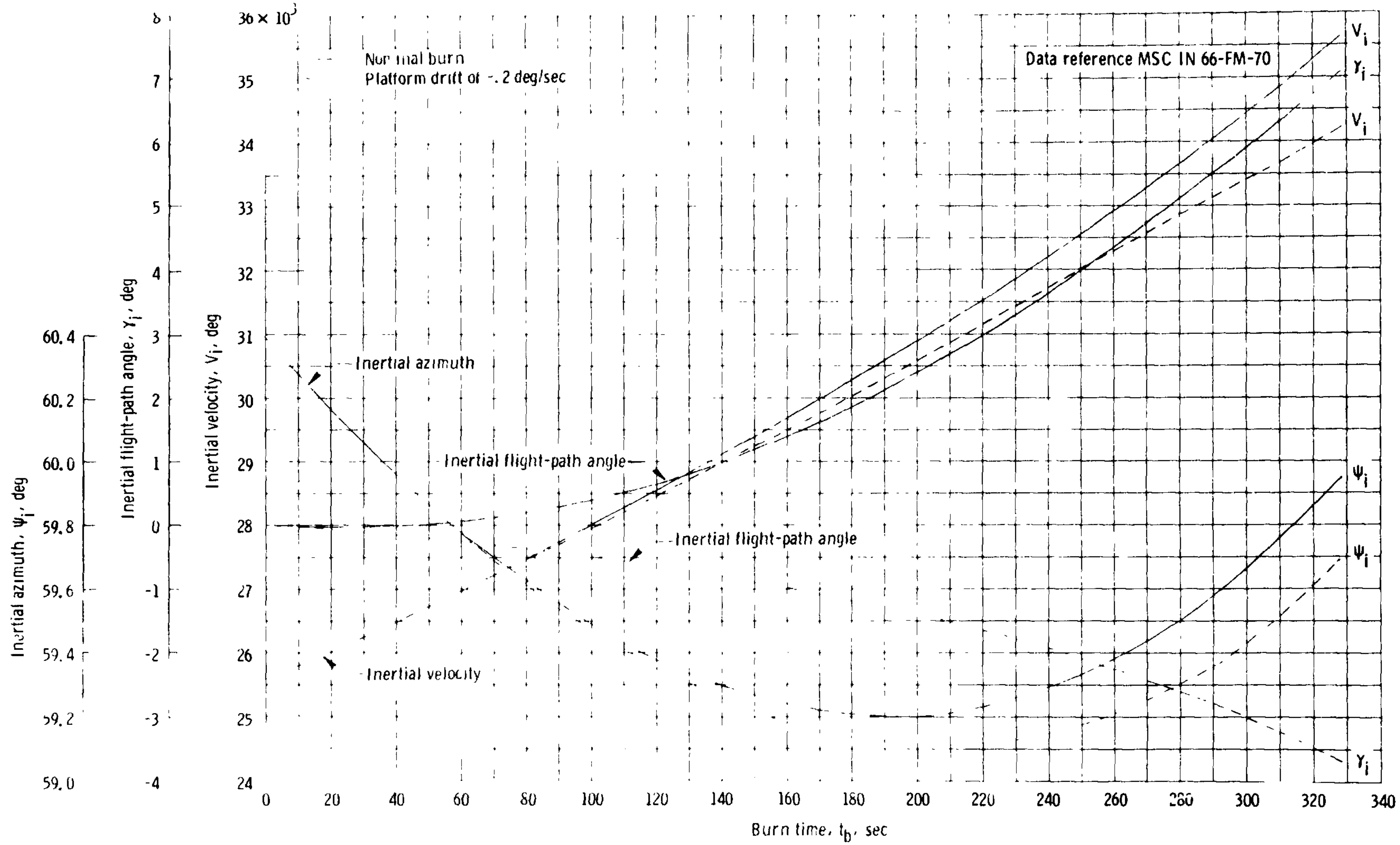


Figure 5.- Inertial velocity, inertial flight-path angle, and inertial azimuth through the translunar injection burn.

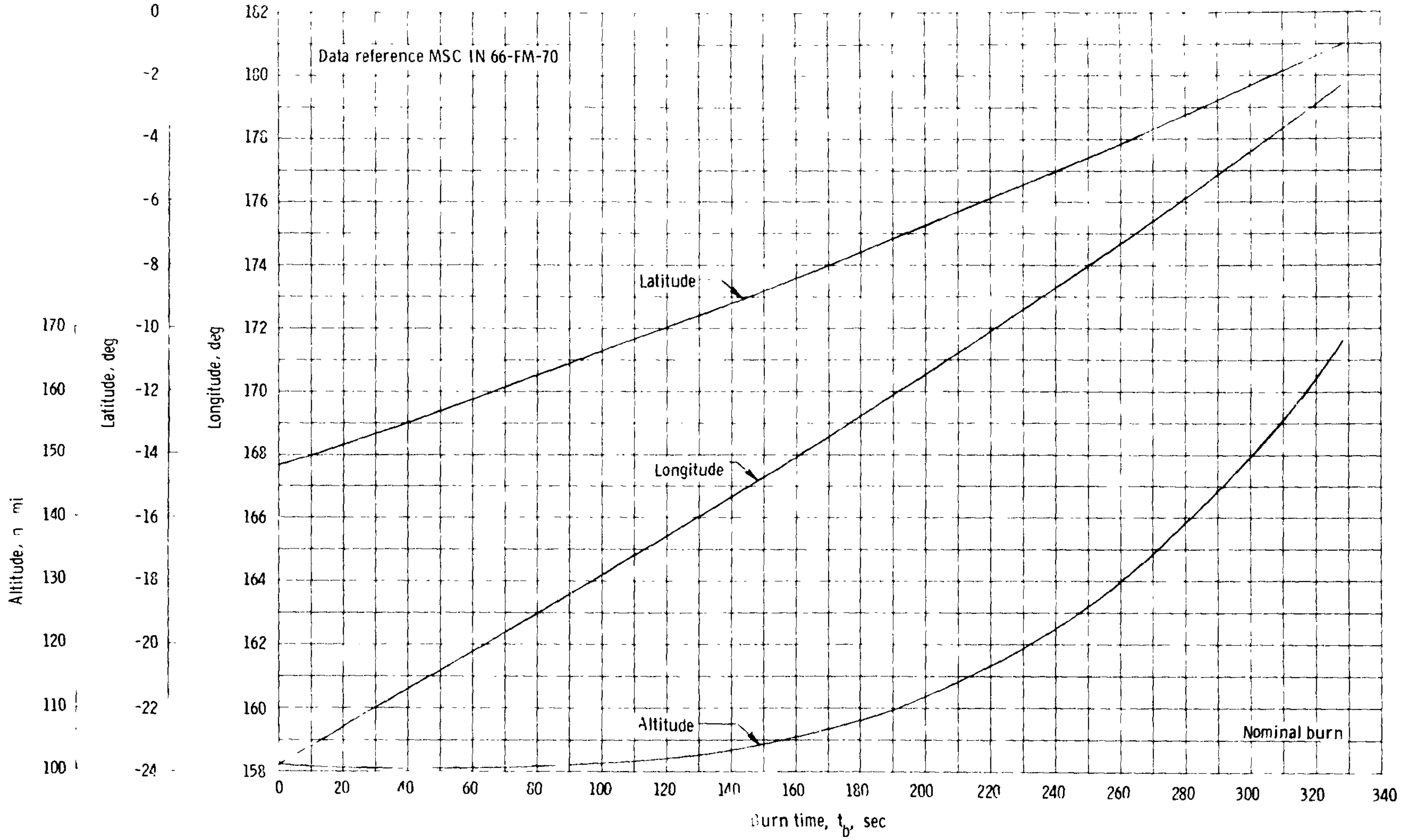


Figure 6. - Latitude, longitude, and altitude through the translunar injection burn.

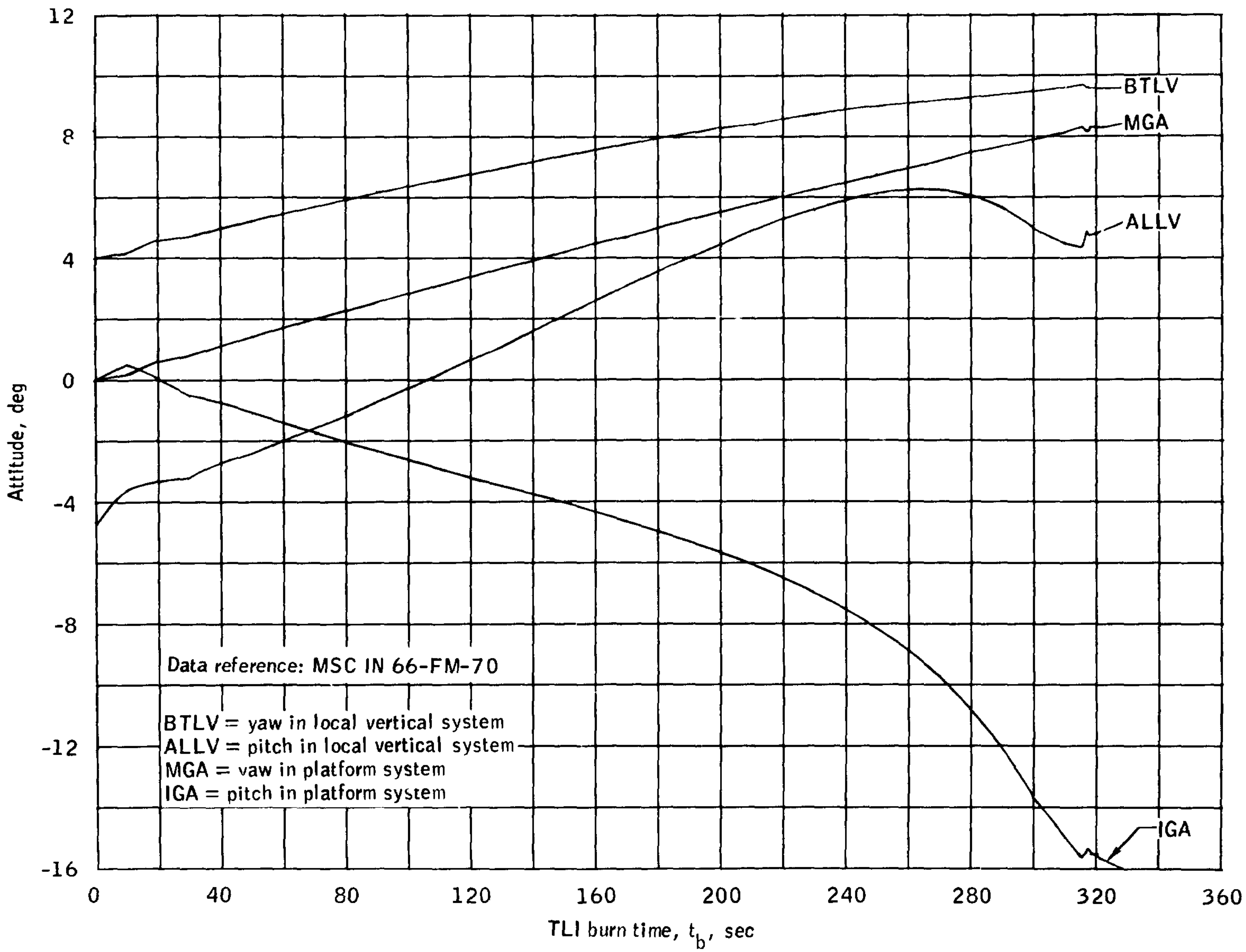


Figure 7.- Launch vehicle attitude through a typical translunar injection maneuver.

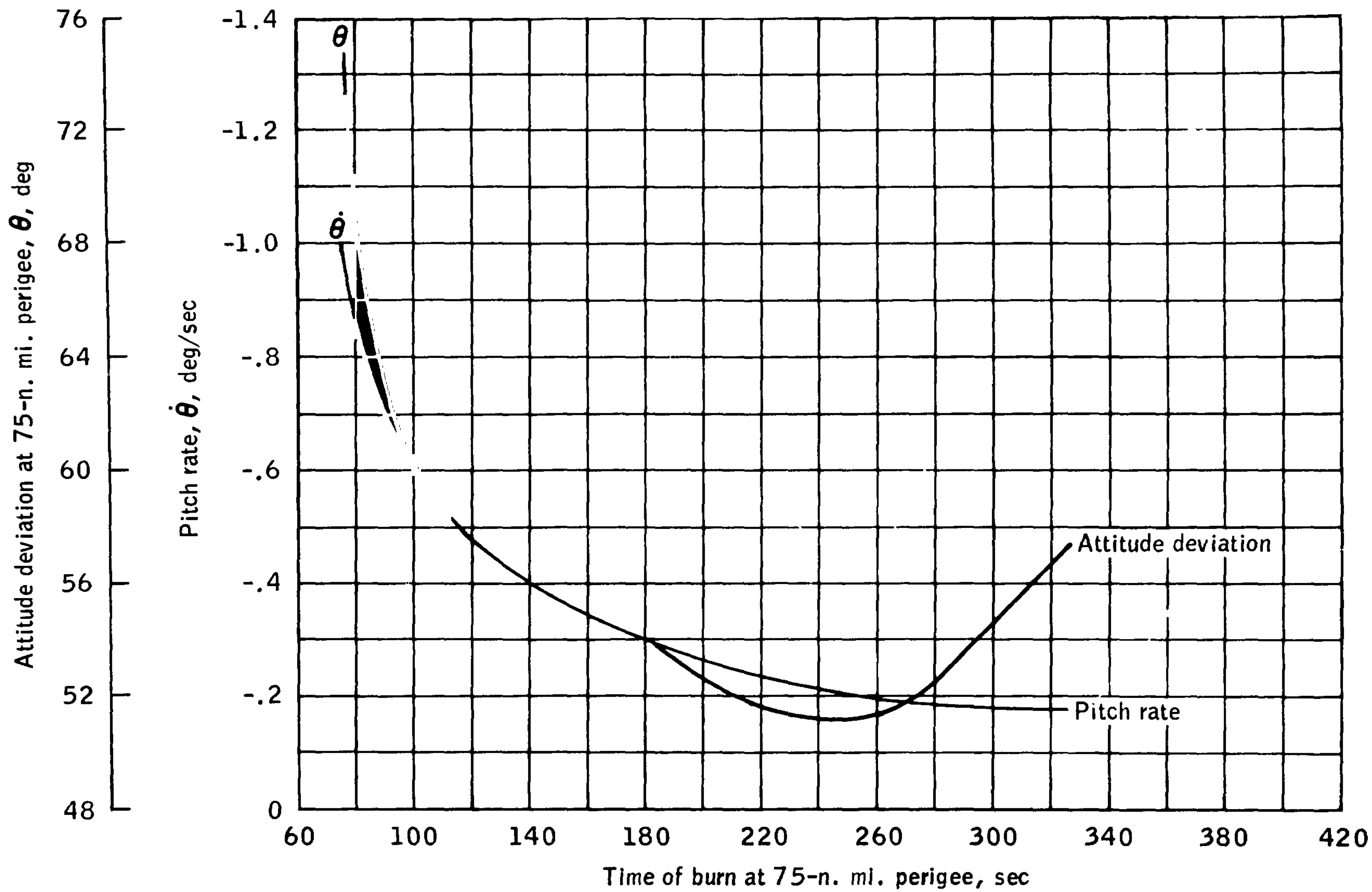
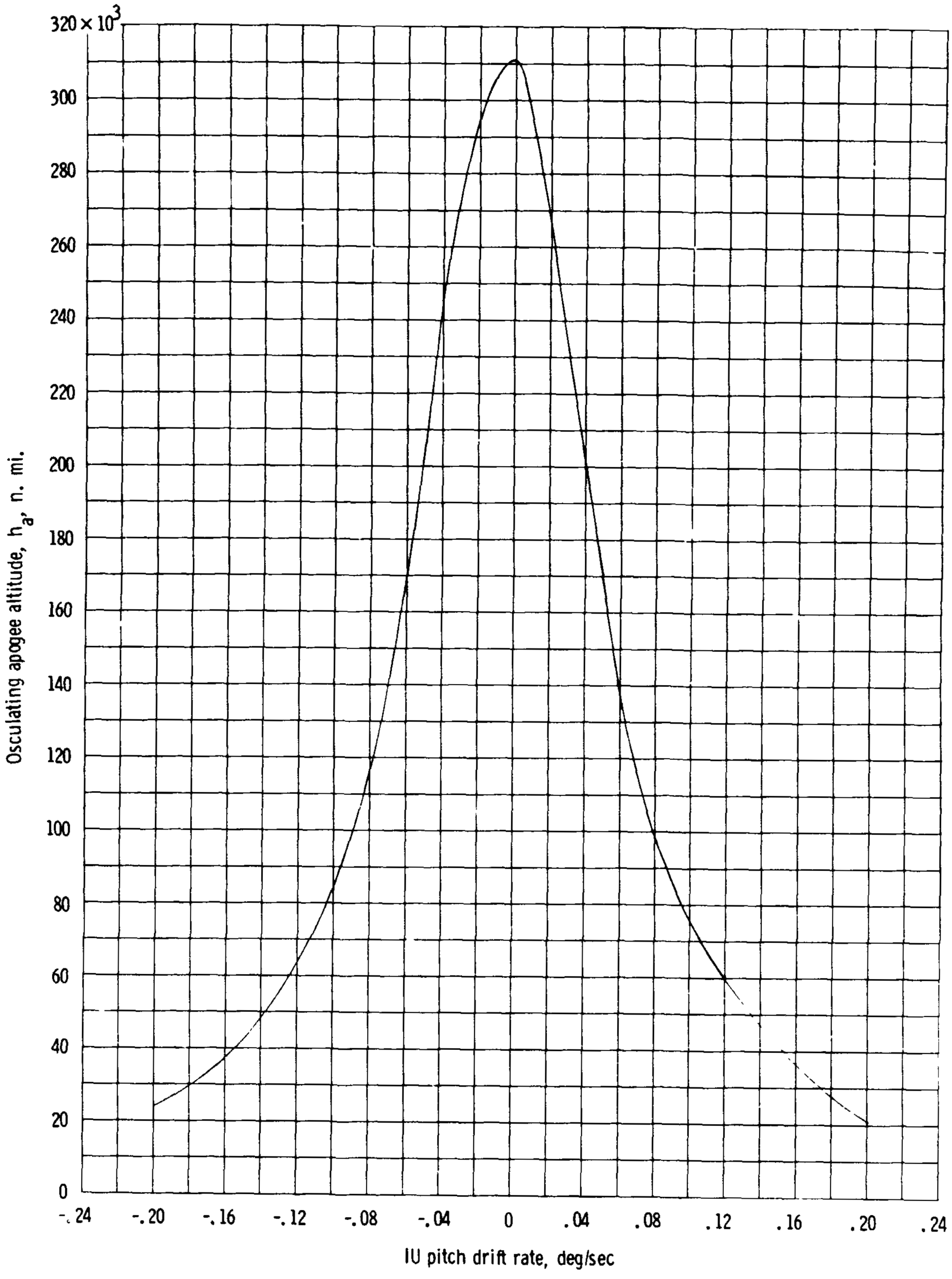
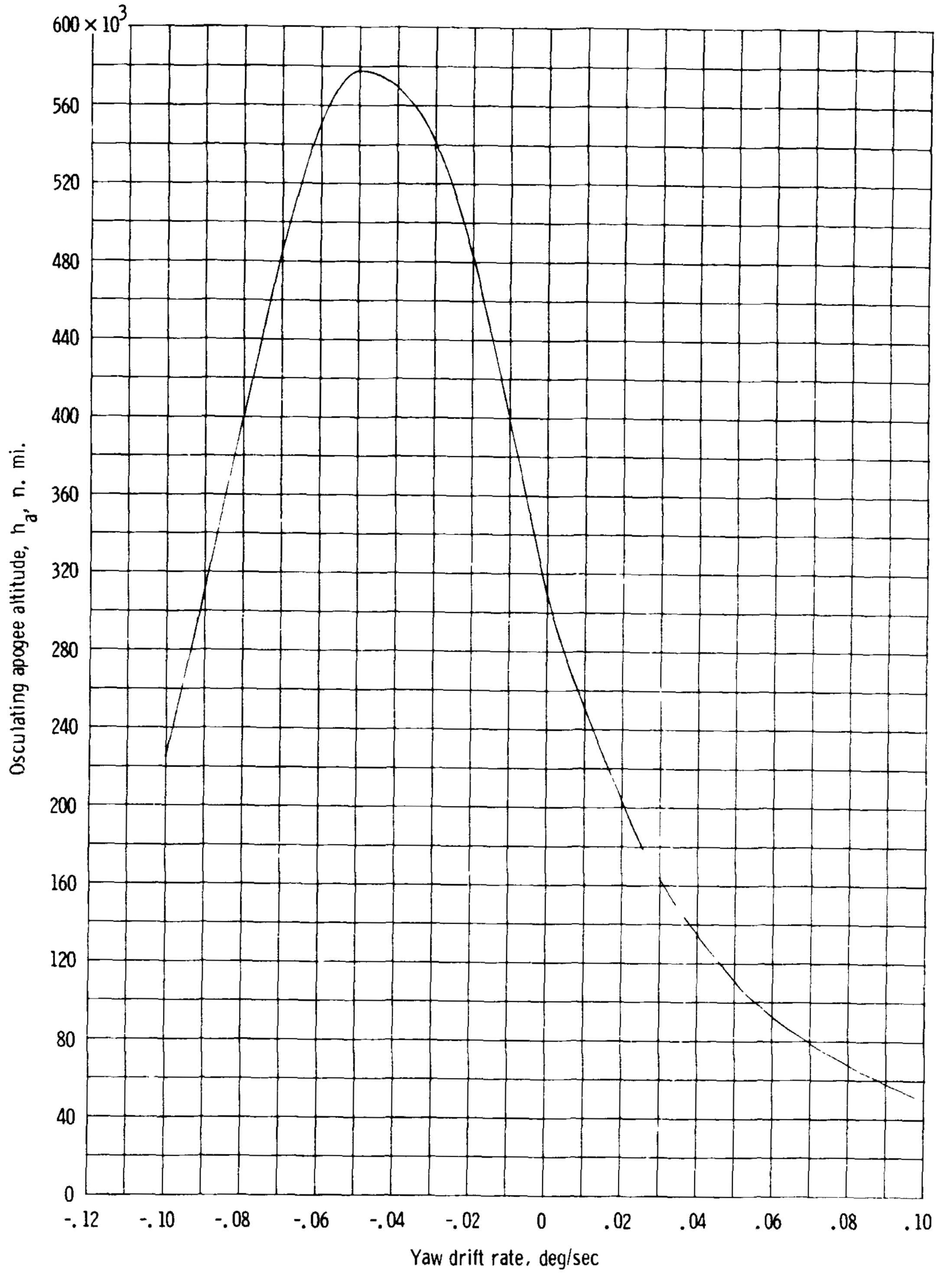


Figure 8.- Maximum allowable attitude deviation to avoid entry after TLI.



(a) Pitch drift rate.

Figure 9. - Osculating apogee altitude as a function of S-IVB platform drift rate.



(b) Yaw drift rate.

Figure 9. - Concluded.

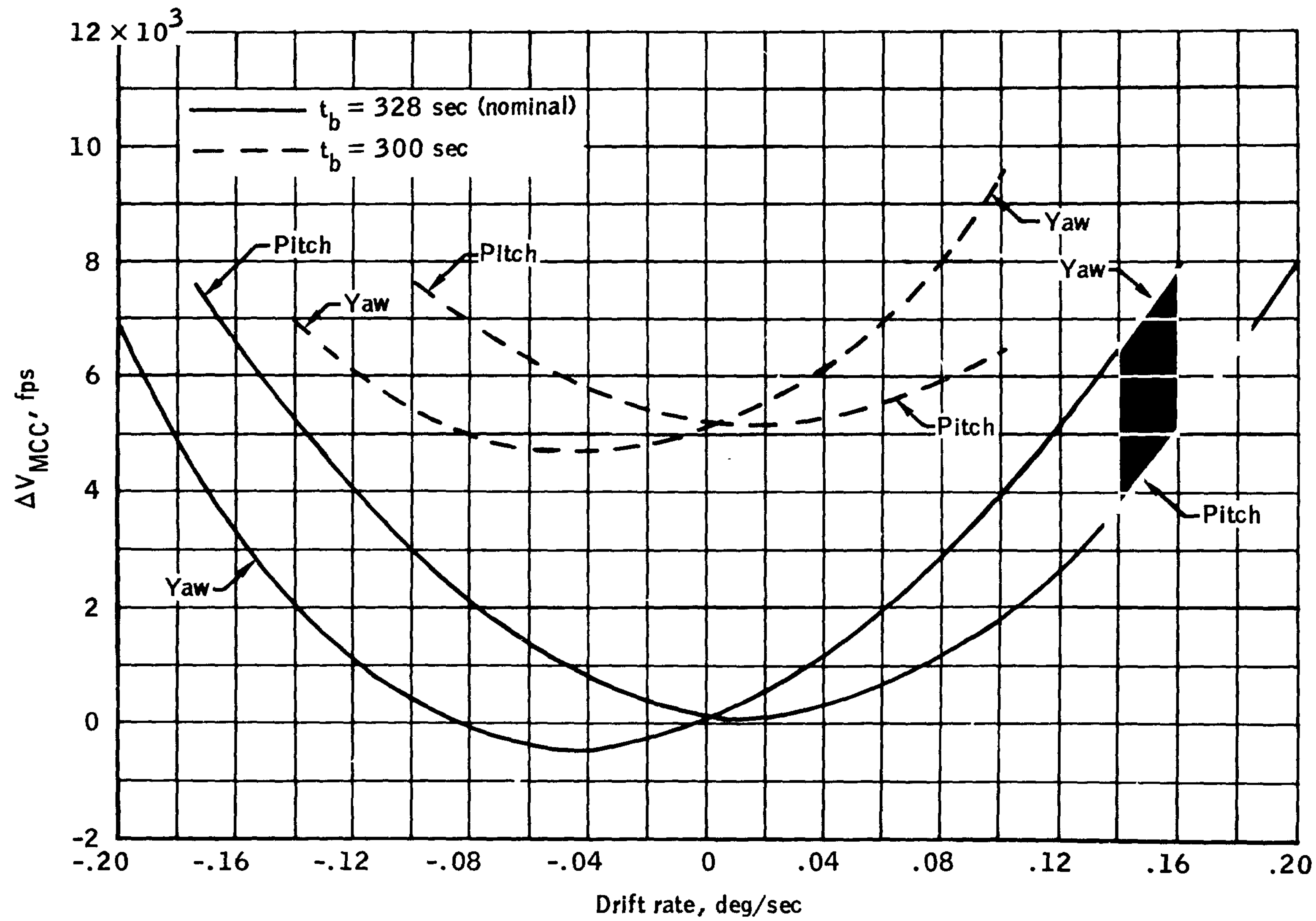


Figure 10.- Allowable drift rates for available alternate mission ΔV.

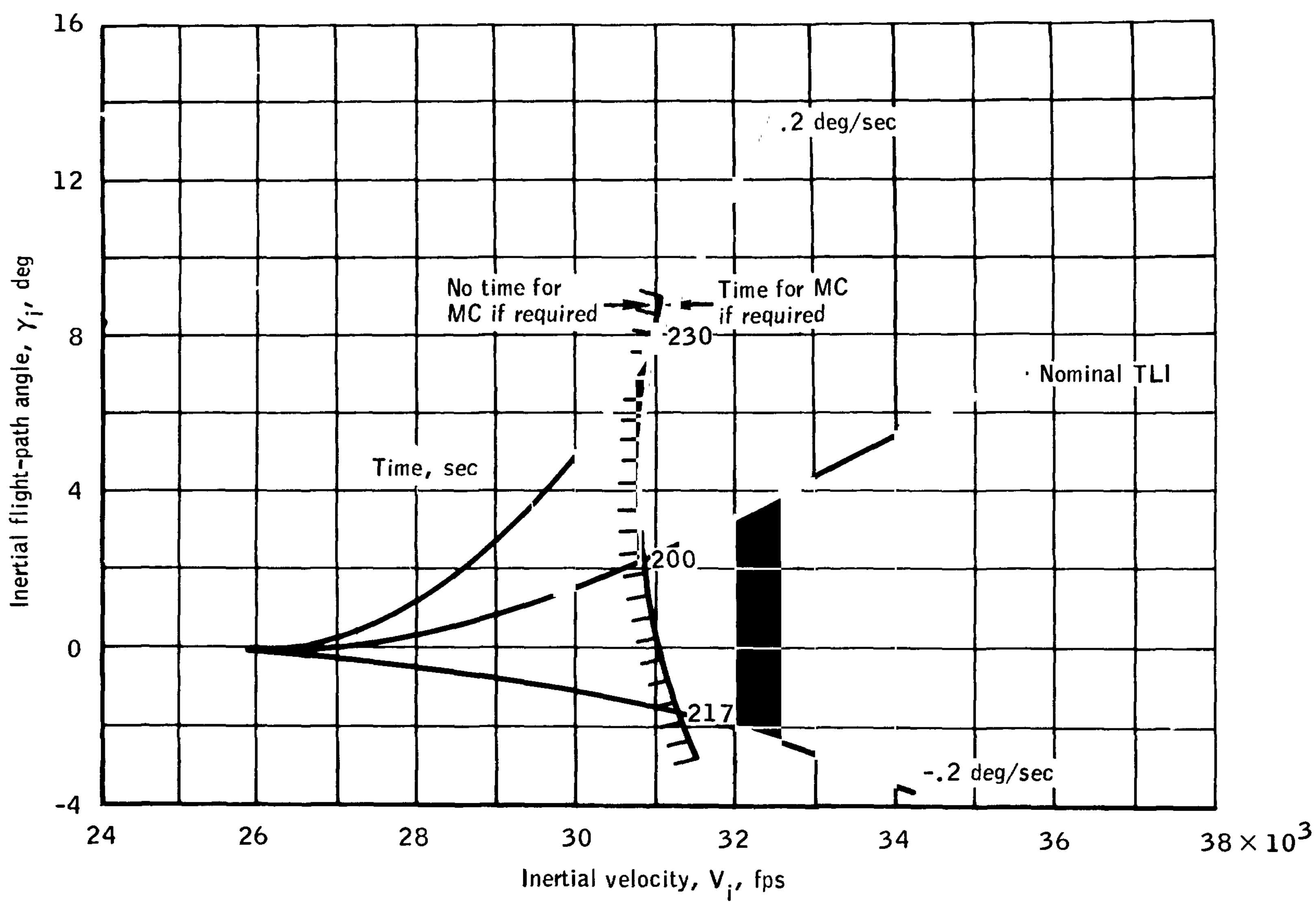


Figure 11.- Entry midcourse time requirement.

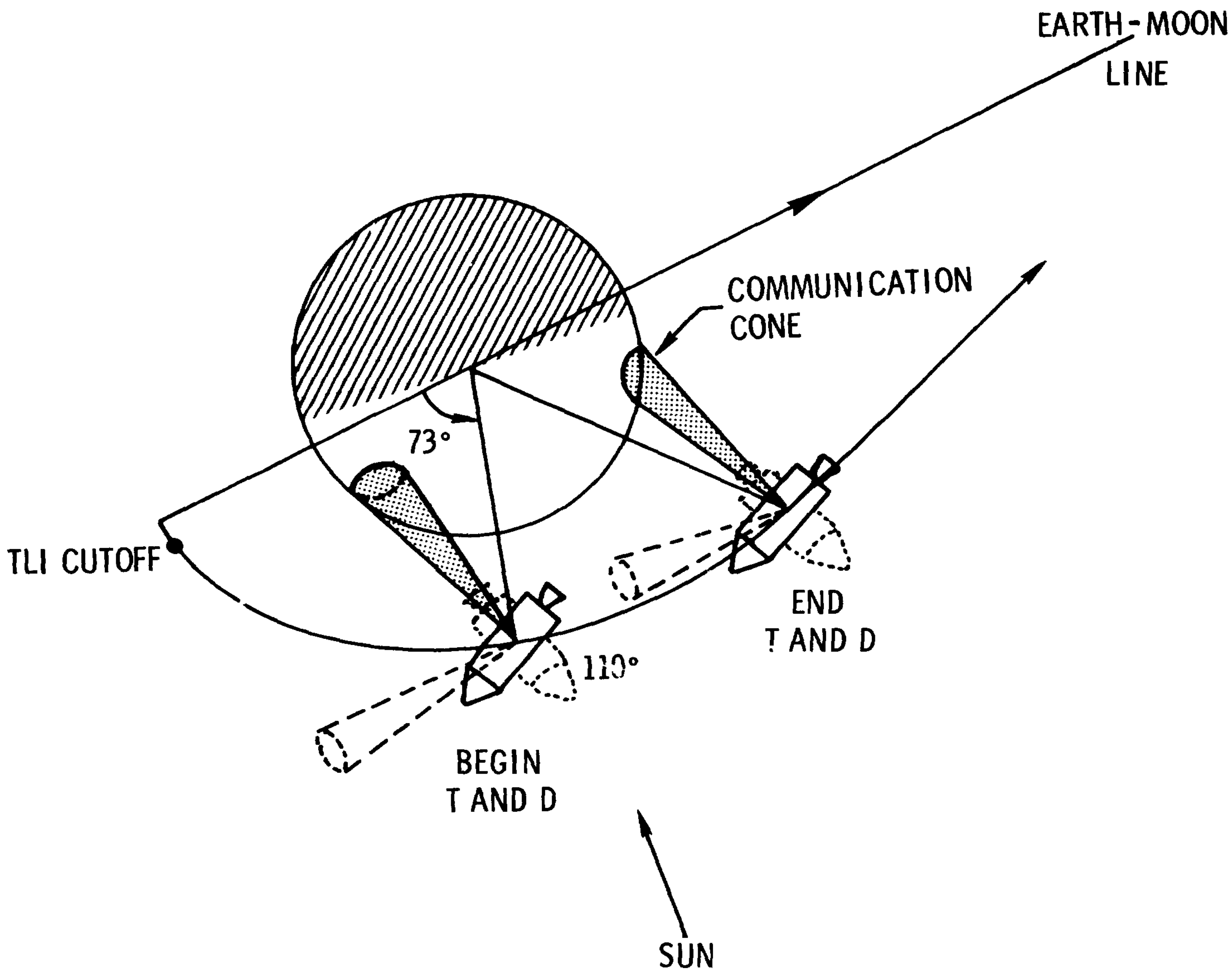


Figure 12.- Communications and lighting considerations.

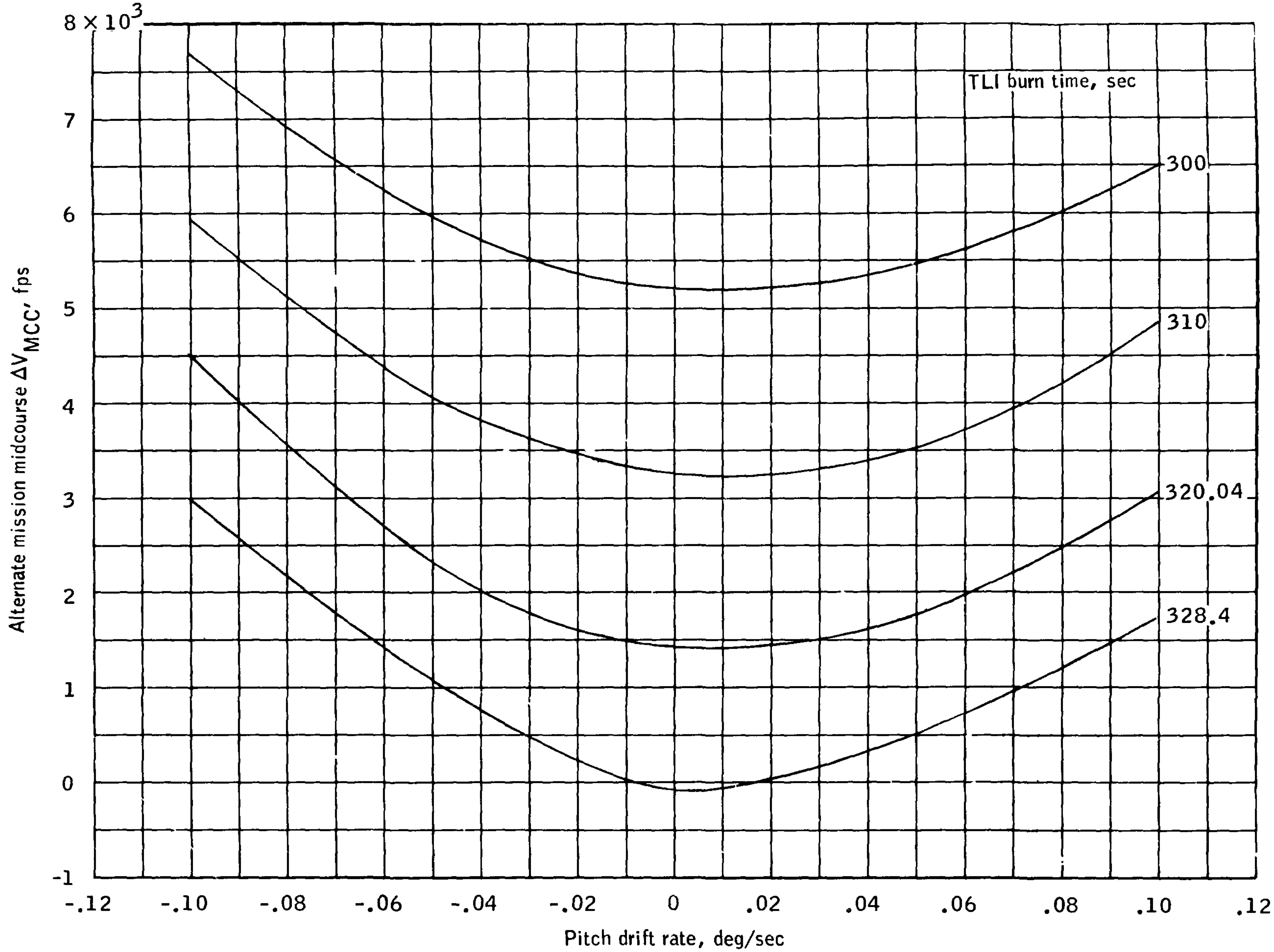


Figure 13.- Alternate mission ΔV_{MCC} as a function of a constant drift rate for various TLI burn times.

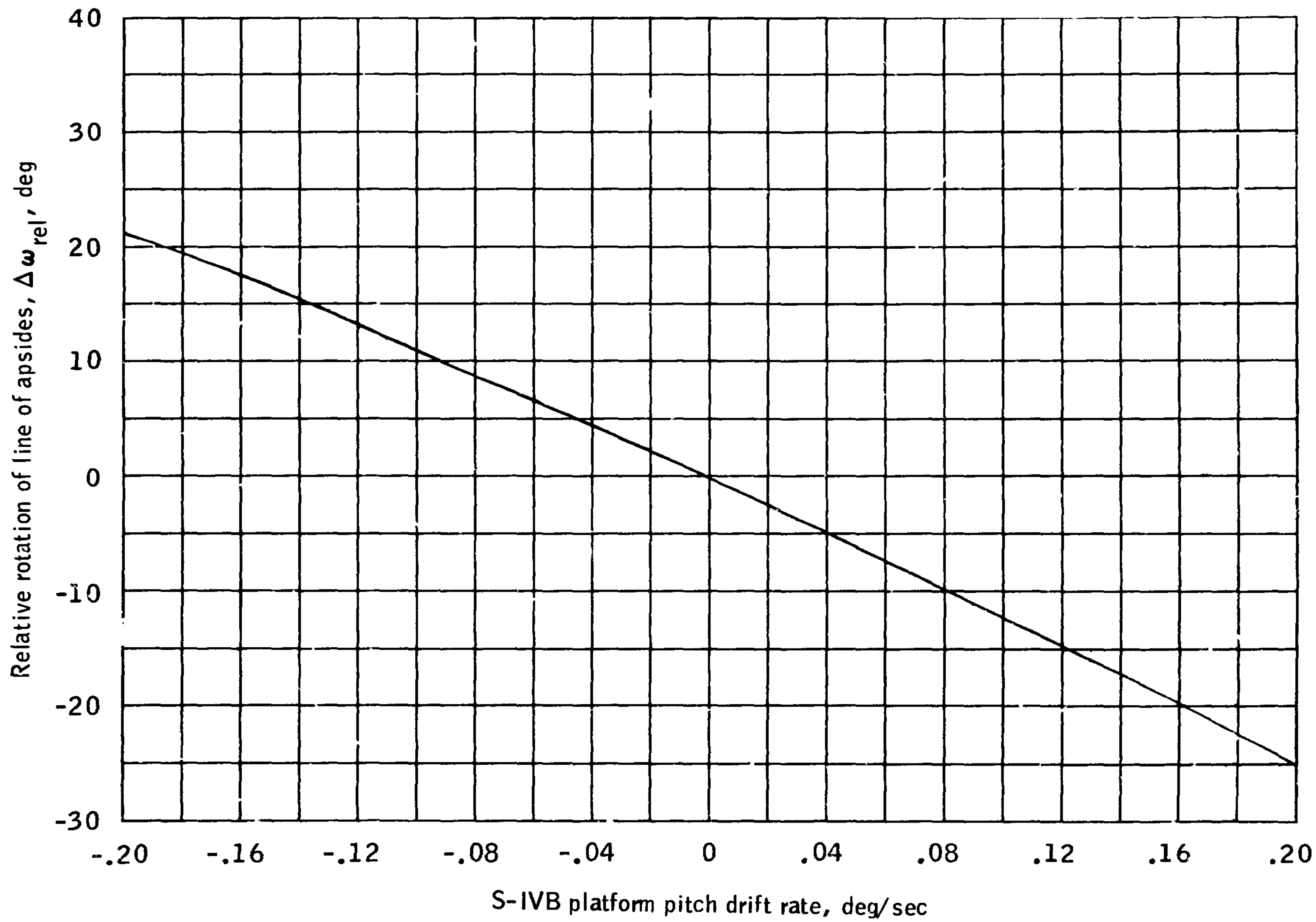


Figure 14.- Deviation from nominal line of apsides as a function of c...stant S-IVB platform drift rates through TLI.

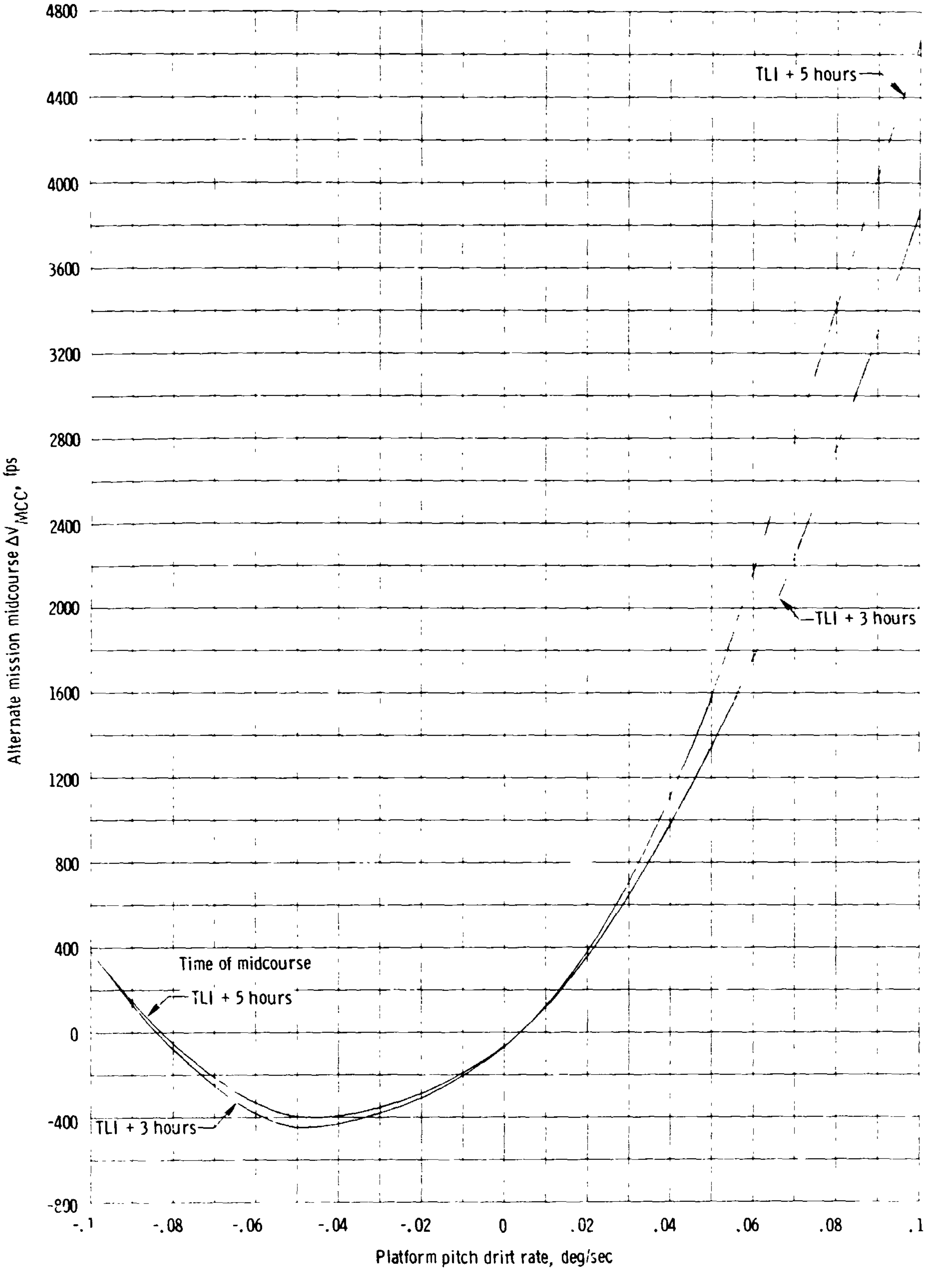


Figure 15.- ΔV_{MCC} as a function of S-IVB platform pitch drift rate for two midcourse correction times.

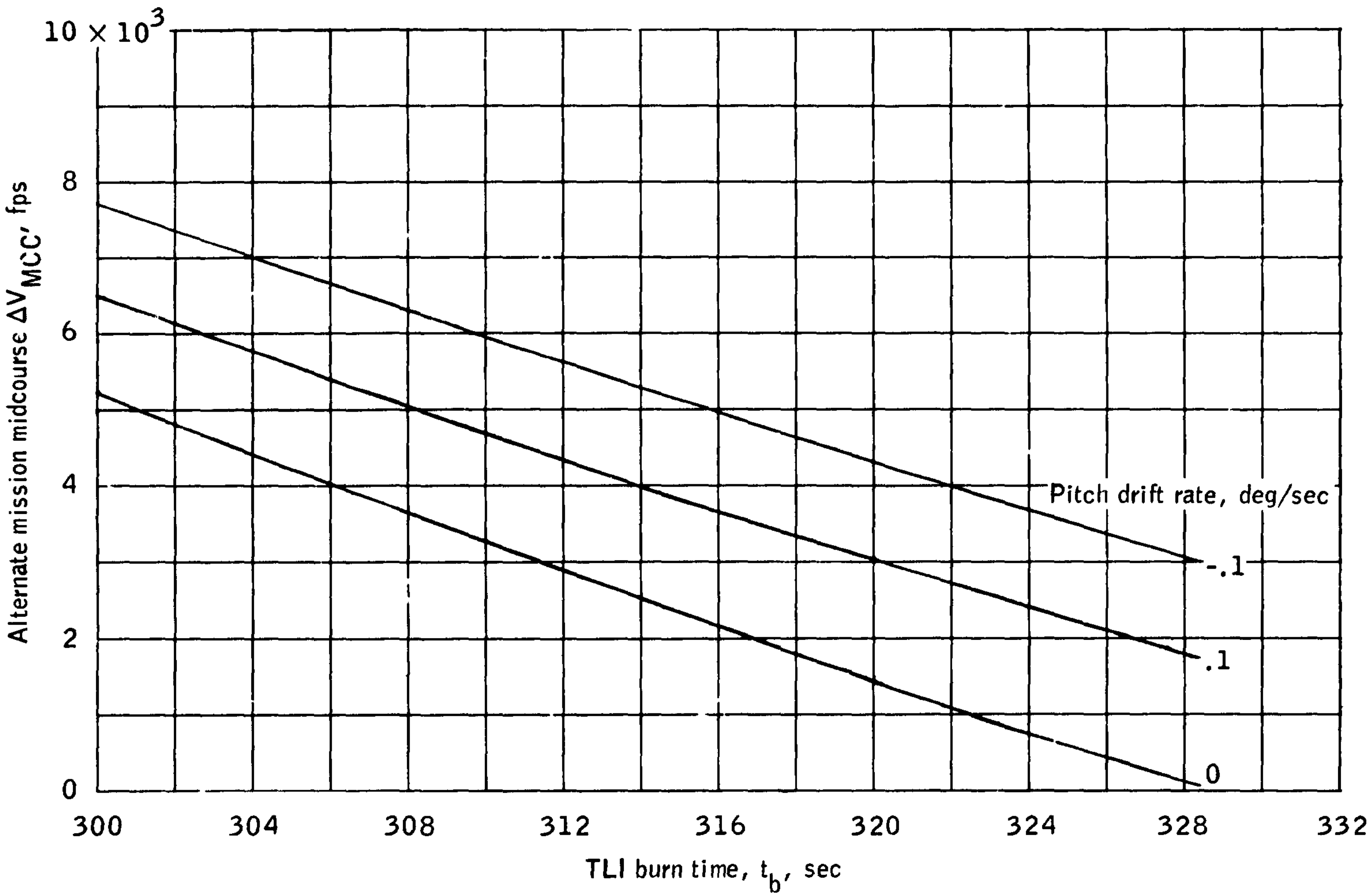


Figure 16. - ΔV_{MCC} as a function of TLI burn time for various pitch drift rates.

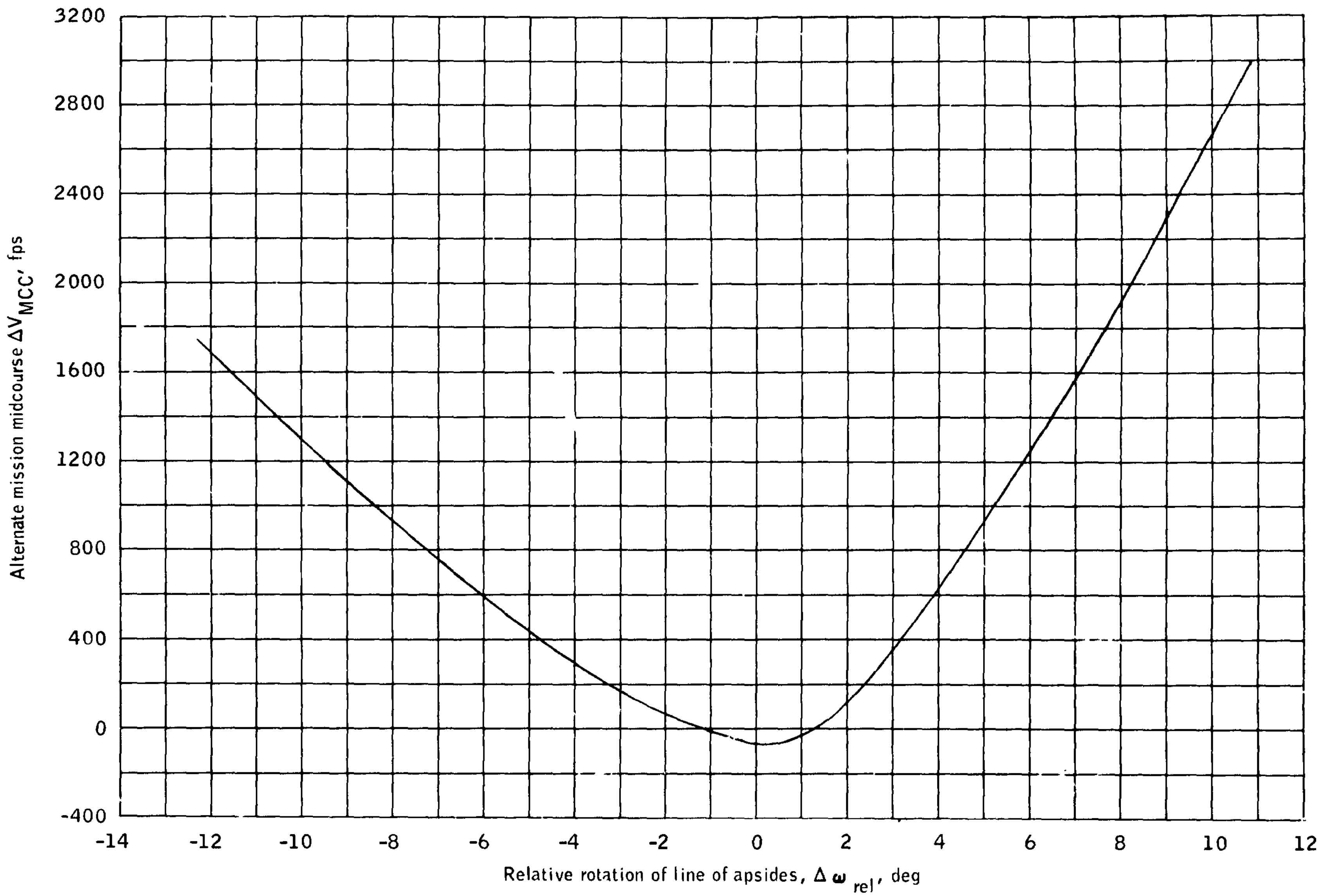


Figure 17.- ΔV_{MCC} as a function of the rotation of the line of apsides from a nominal TLI cutoff orientation.

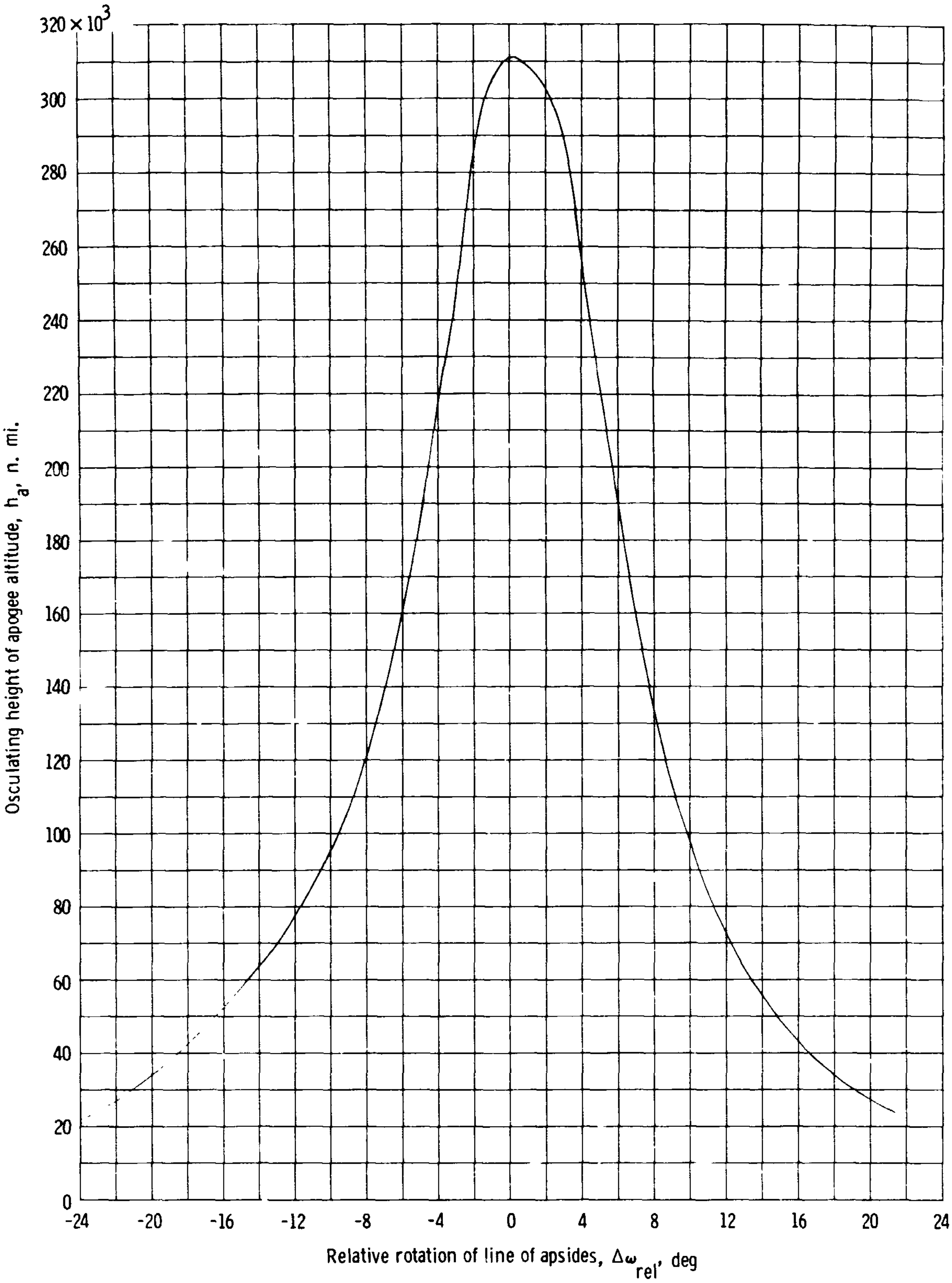


Figure 18. - Osculating apogee altitude as a function of the rotation of the line of apsides from a nominal TLI cutoff orientation.

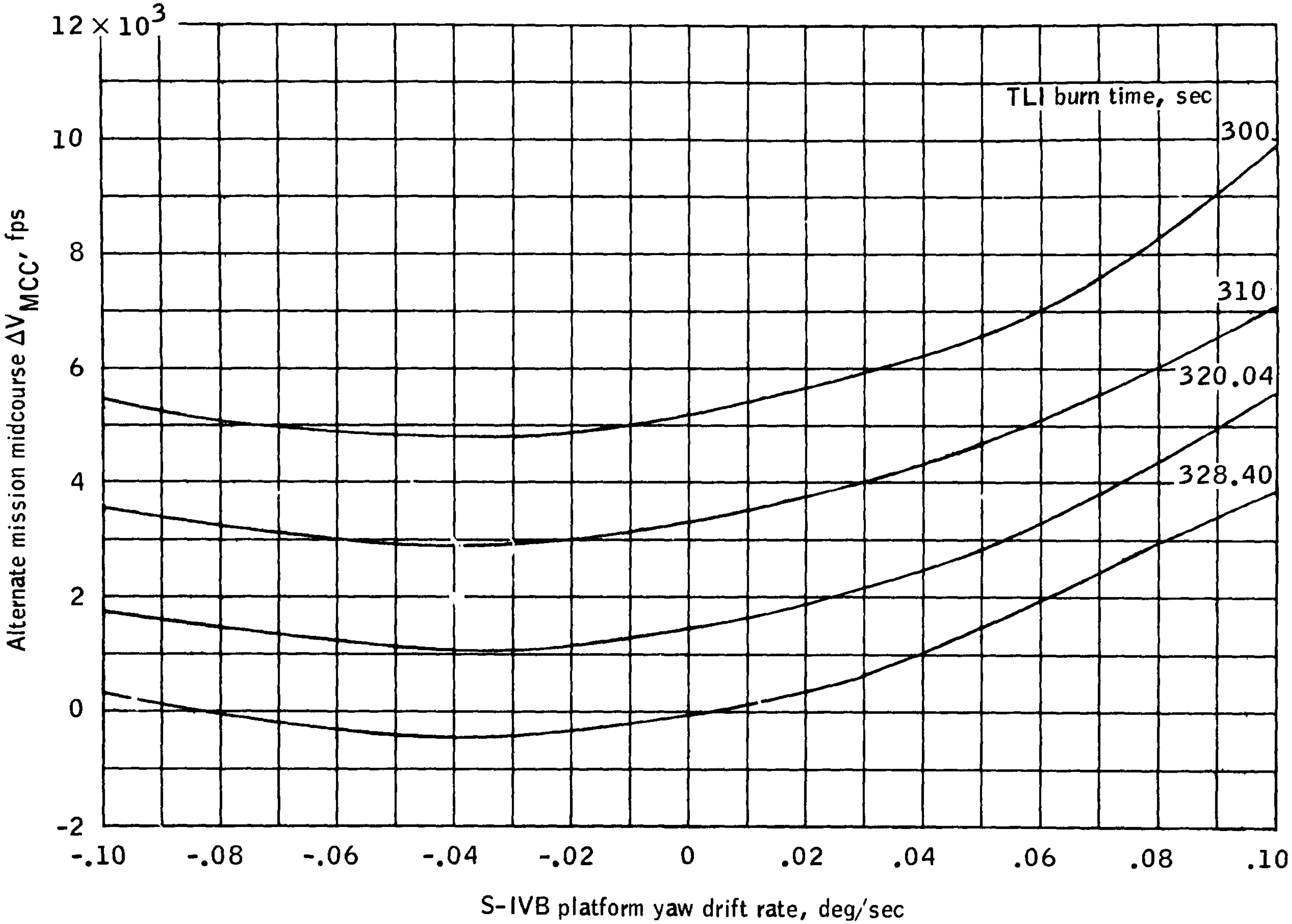


Figure 19.- Alternate mission ΔV_{MCC} as a function of a constant drift rate for various TLI burn times.

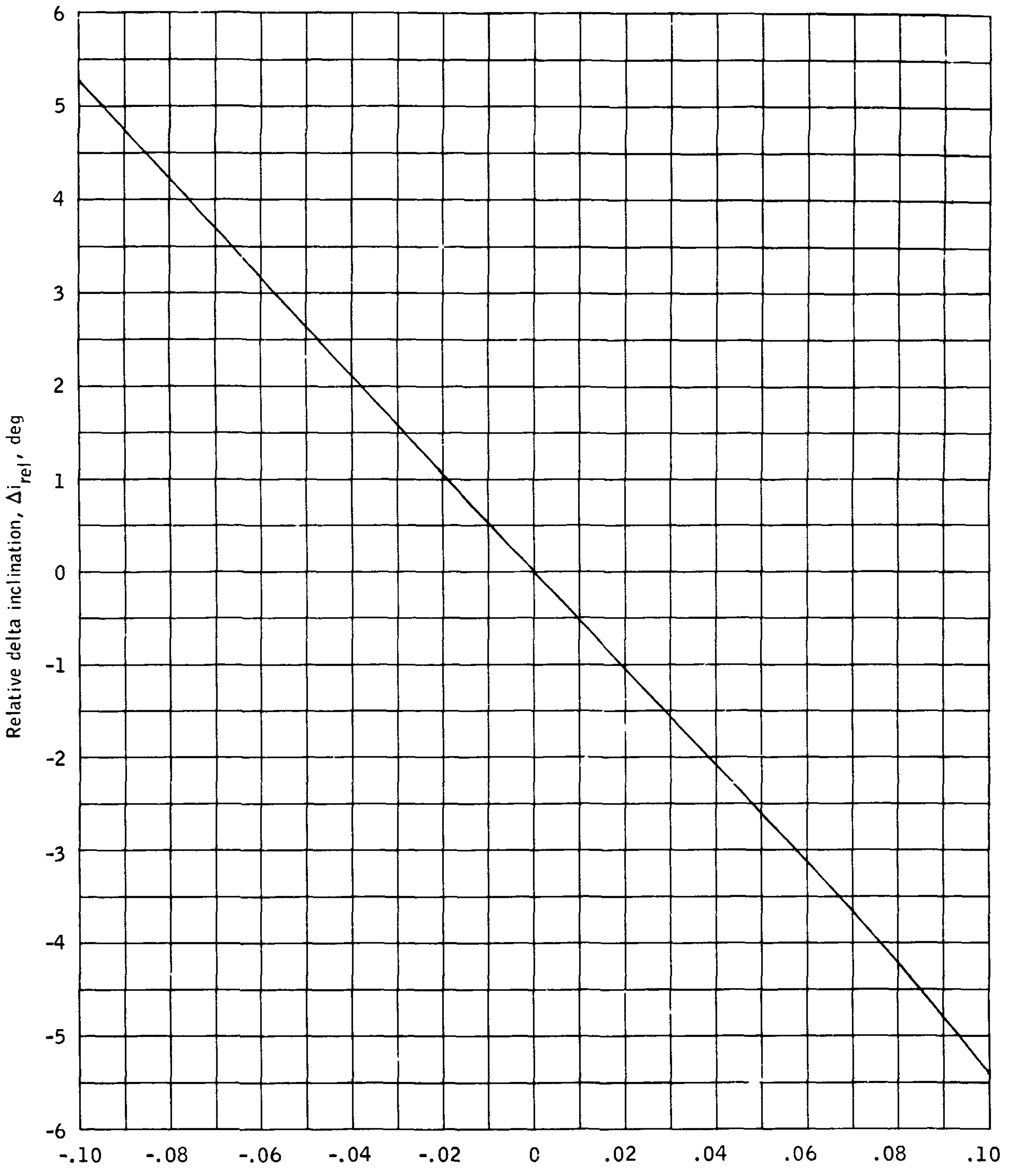


Figure 20.- Deviation from nominal inclination as a function of constant S-IVB platform drift rates through TLI.

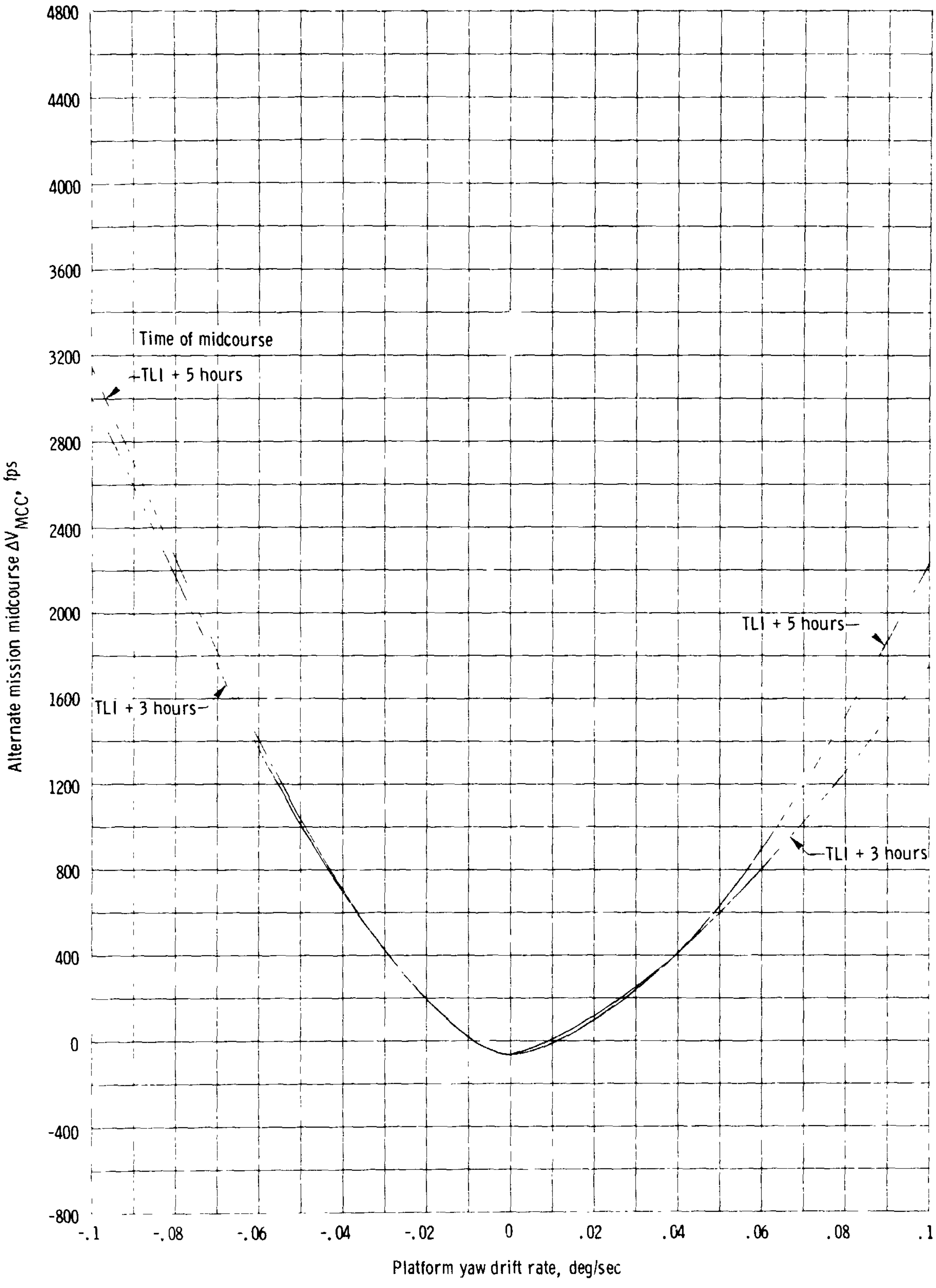


Figure 21. - ΔV_{MCC} as a function of S-IVB platform yaw drift rates for two midcourse times.

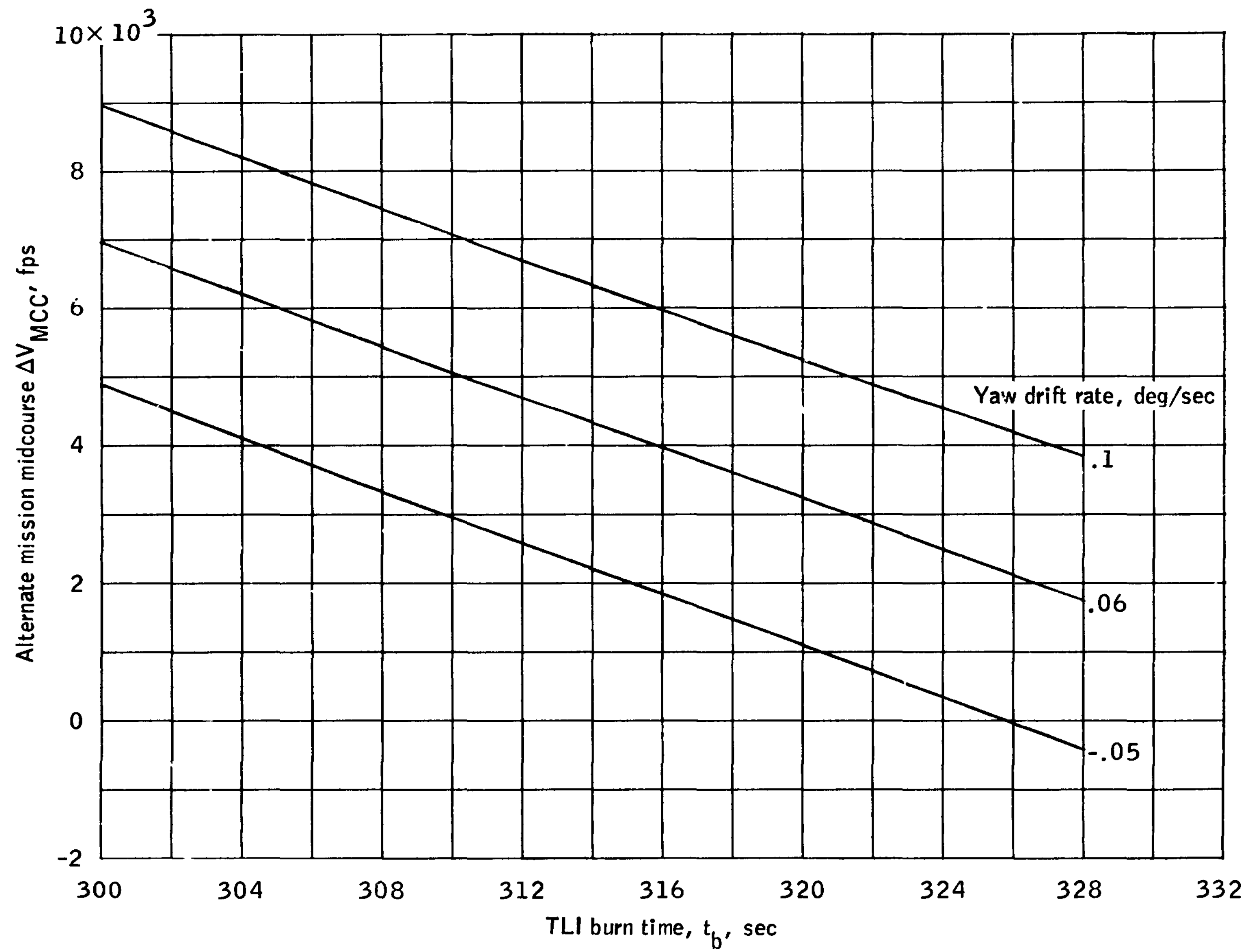


Figure 22.- ΔV_{MCC} as a function of TLI burn time for various yaw drift rates.

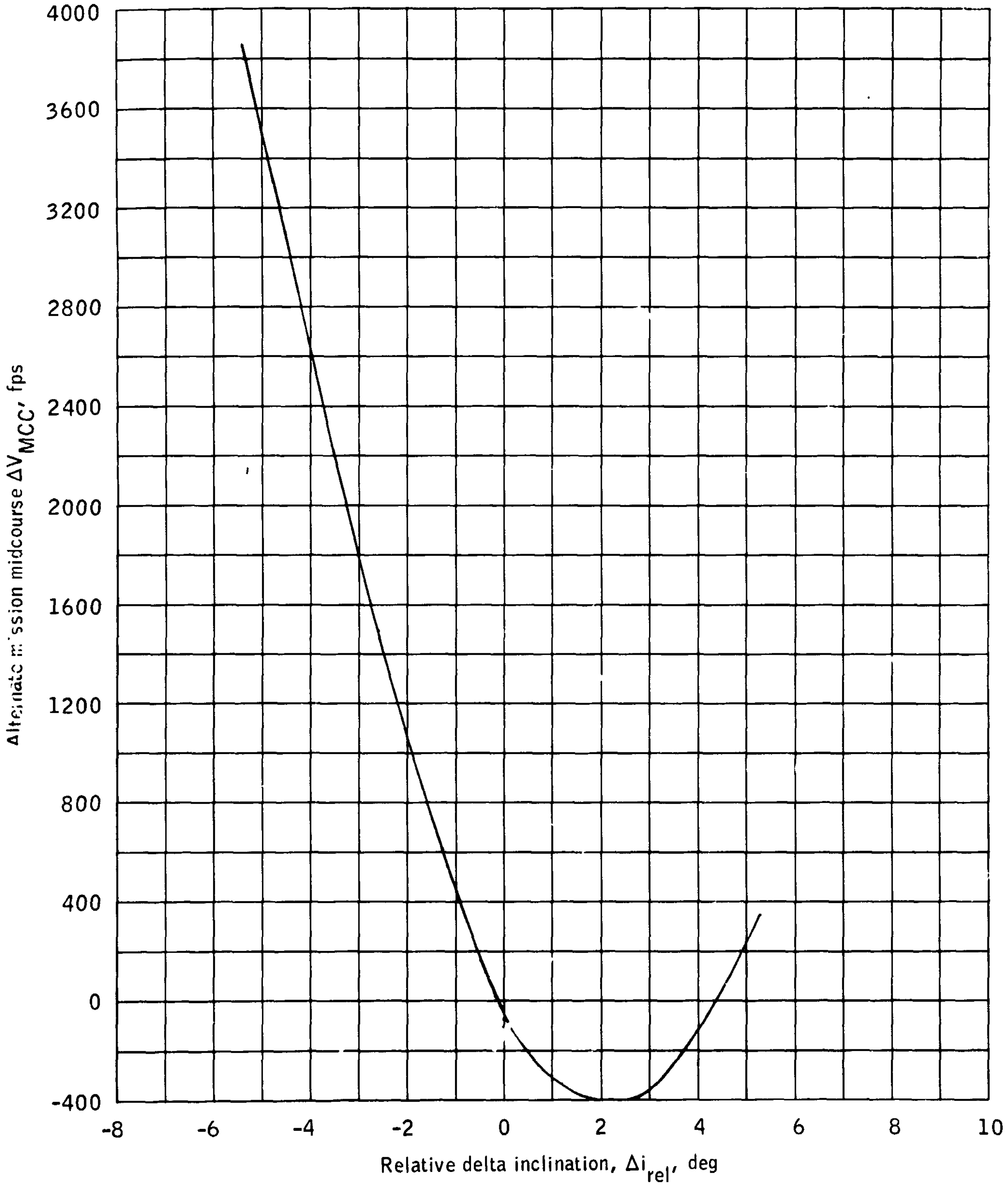


Figure 23.- ΔV_{MCC} as a function of delta inclination from a nominal TLI cutoff orientation.

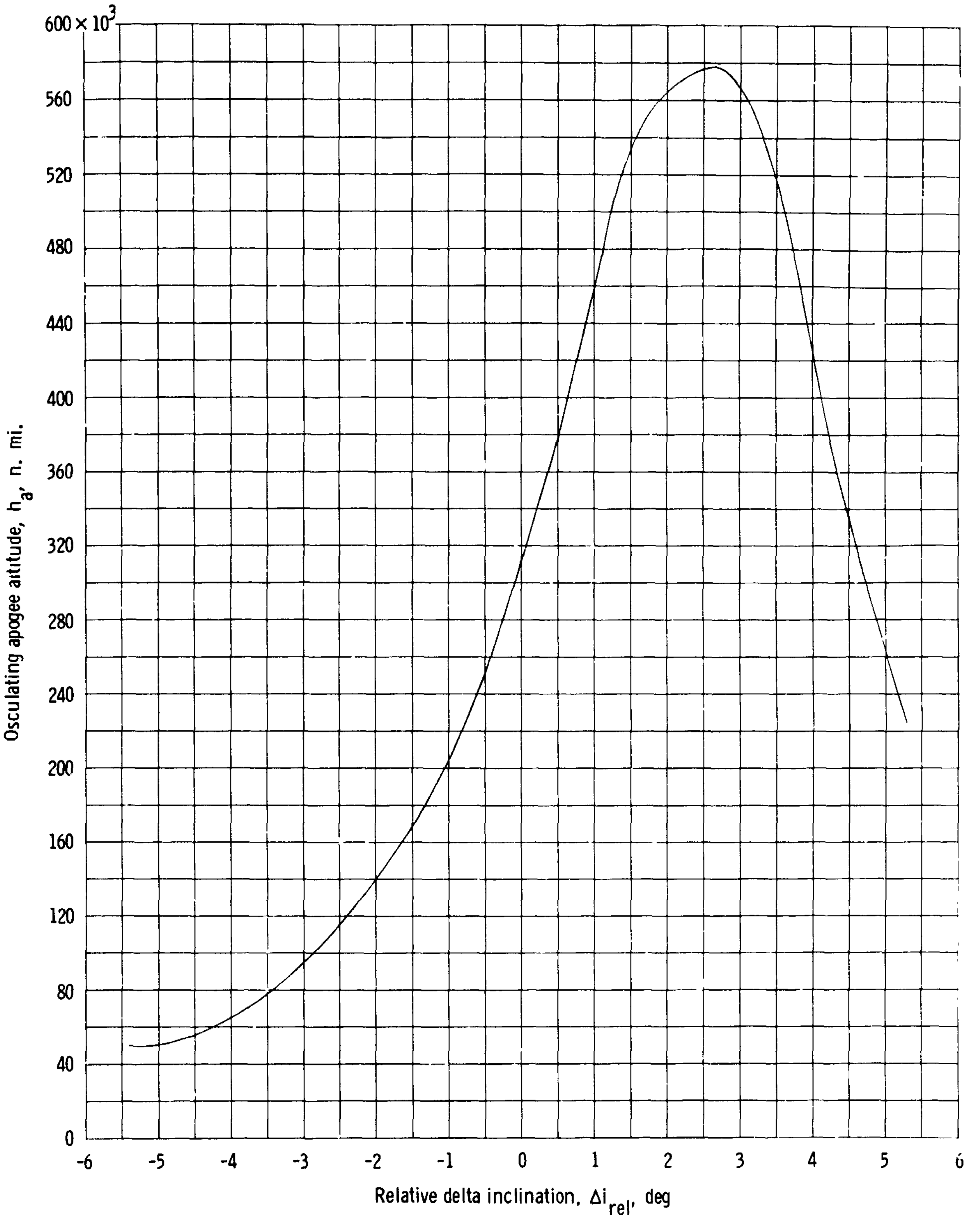


Figure 24. - Osculating apogee altitude as a function of delta inclination from a nominal TLI cutoff orientation.

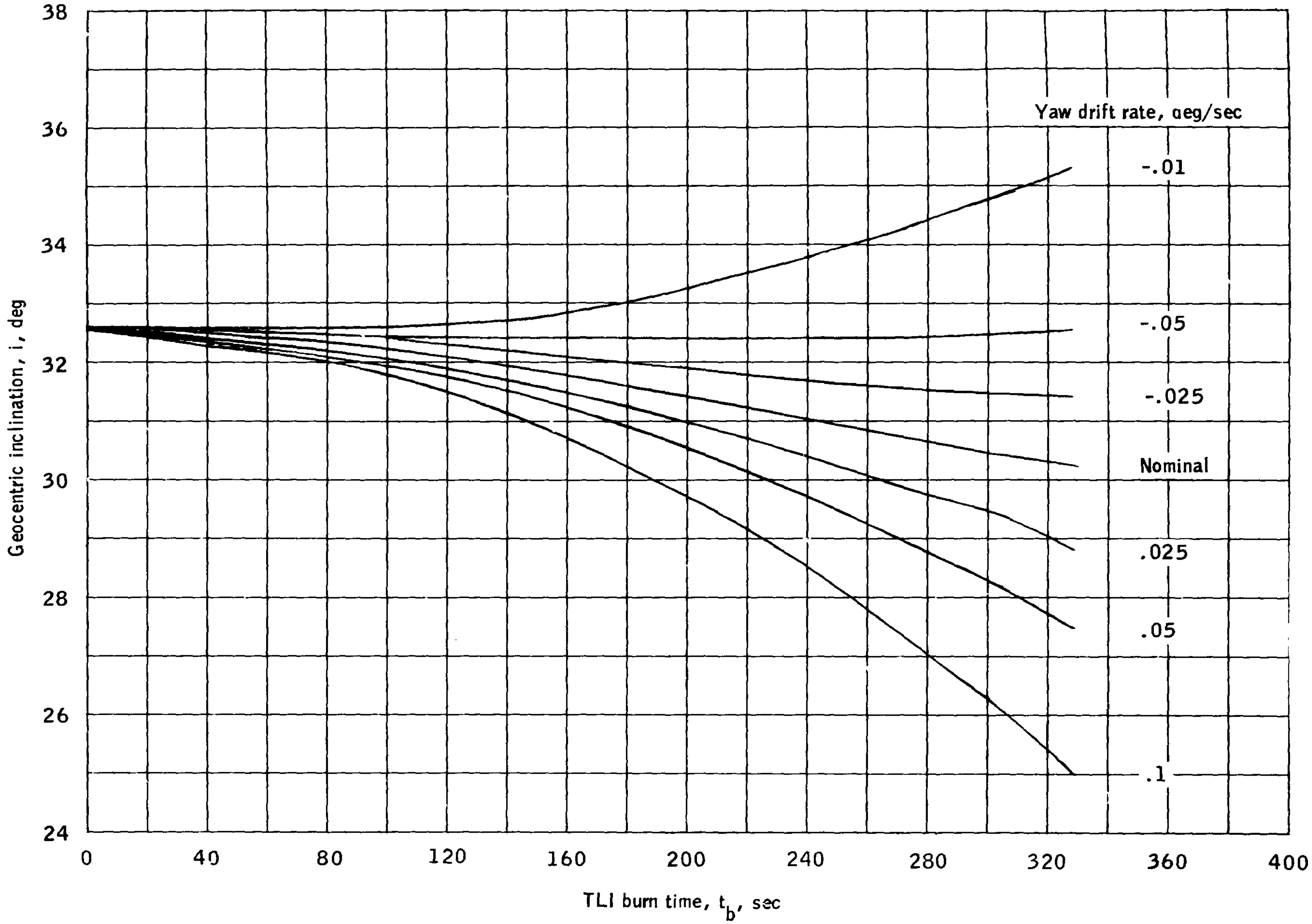


Figure 25.- Geocentric inclination time histories for various yaw drift rates.

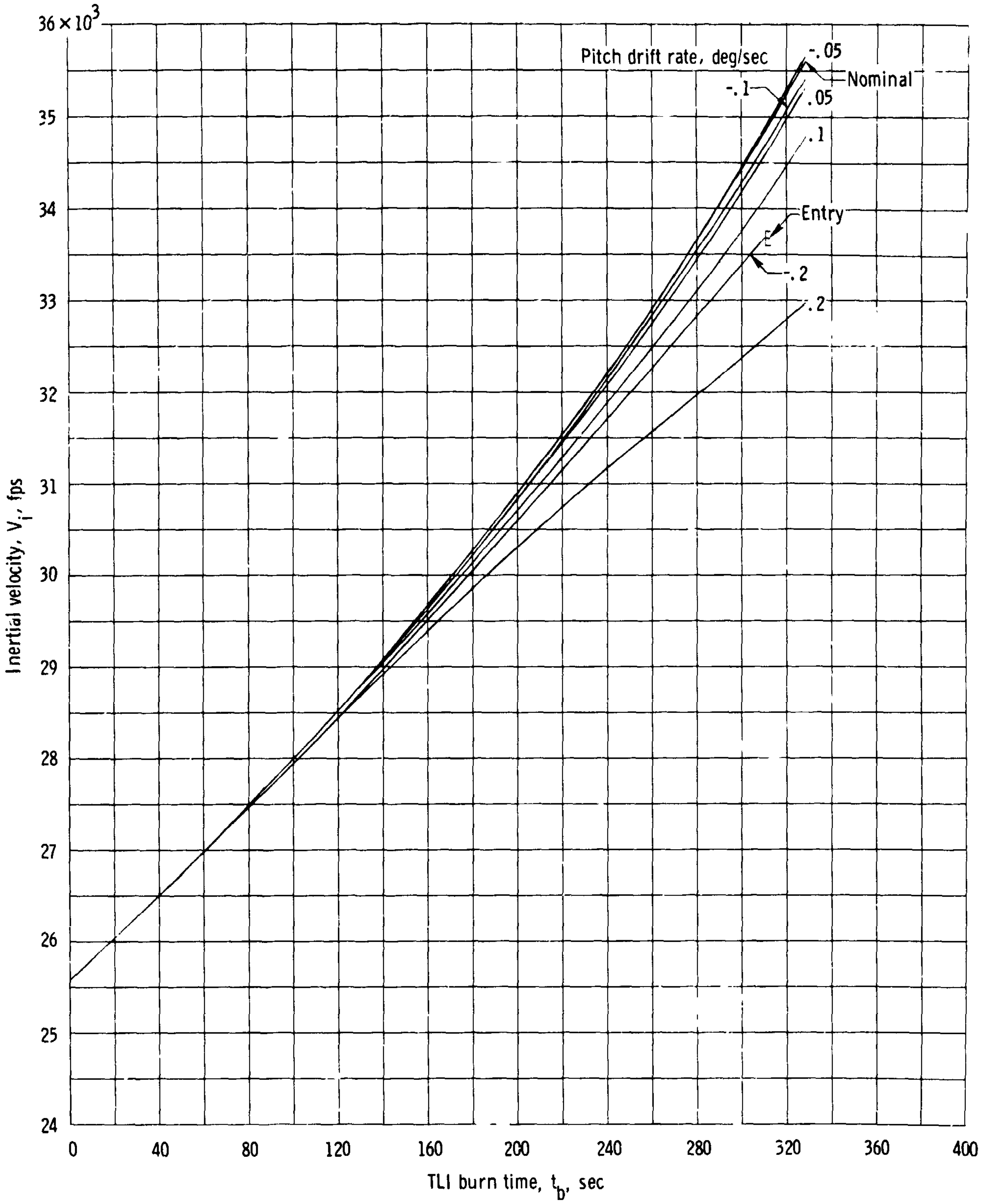


Figure 26. - Inertial velocity time histories for various pitch drift rates.

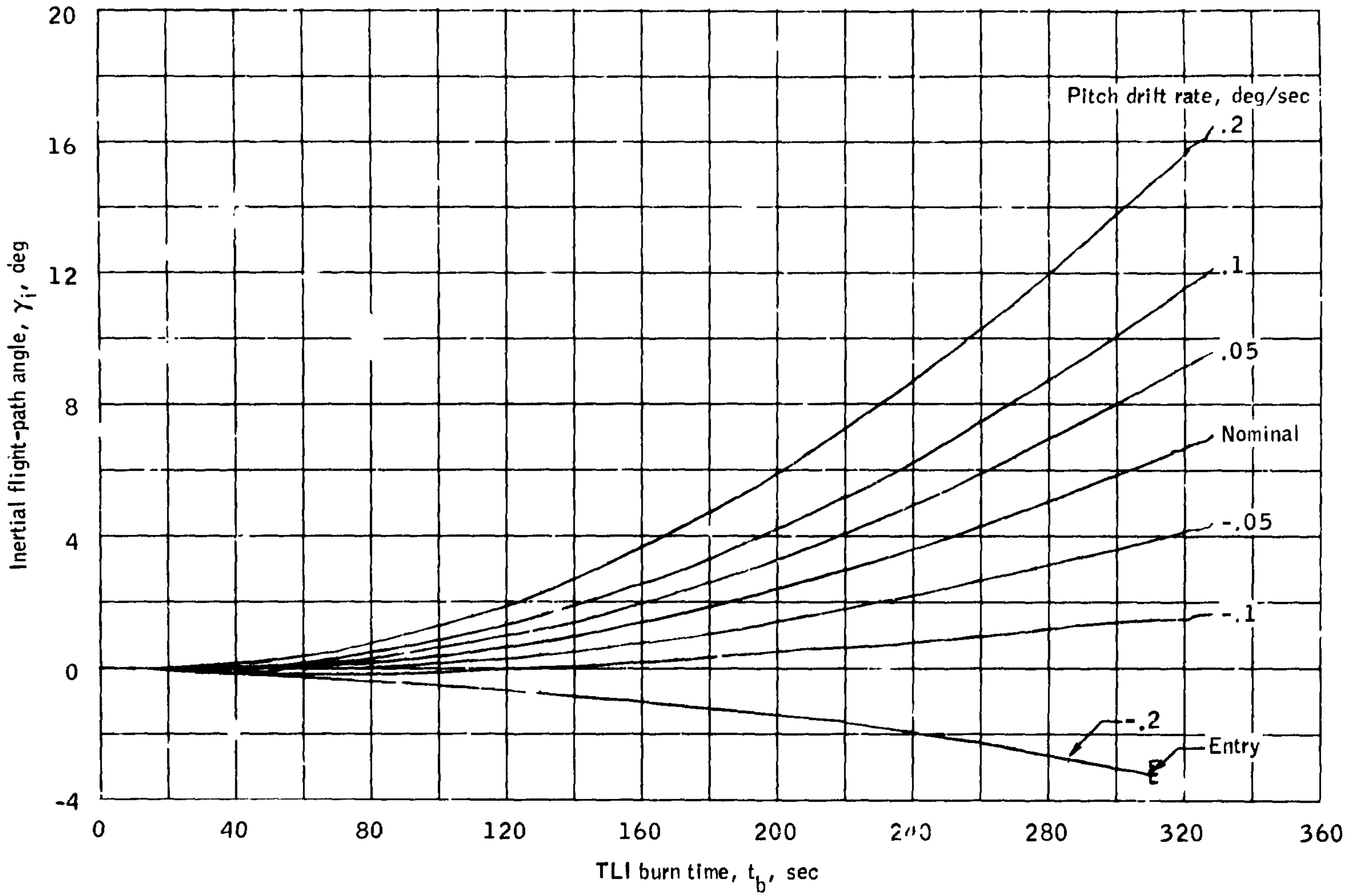


Figure 27.- Inertial flight-path angle time histories for various pitch drift rates.

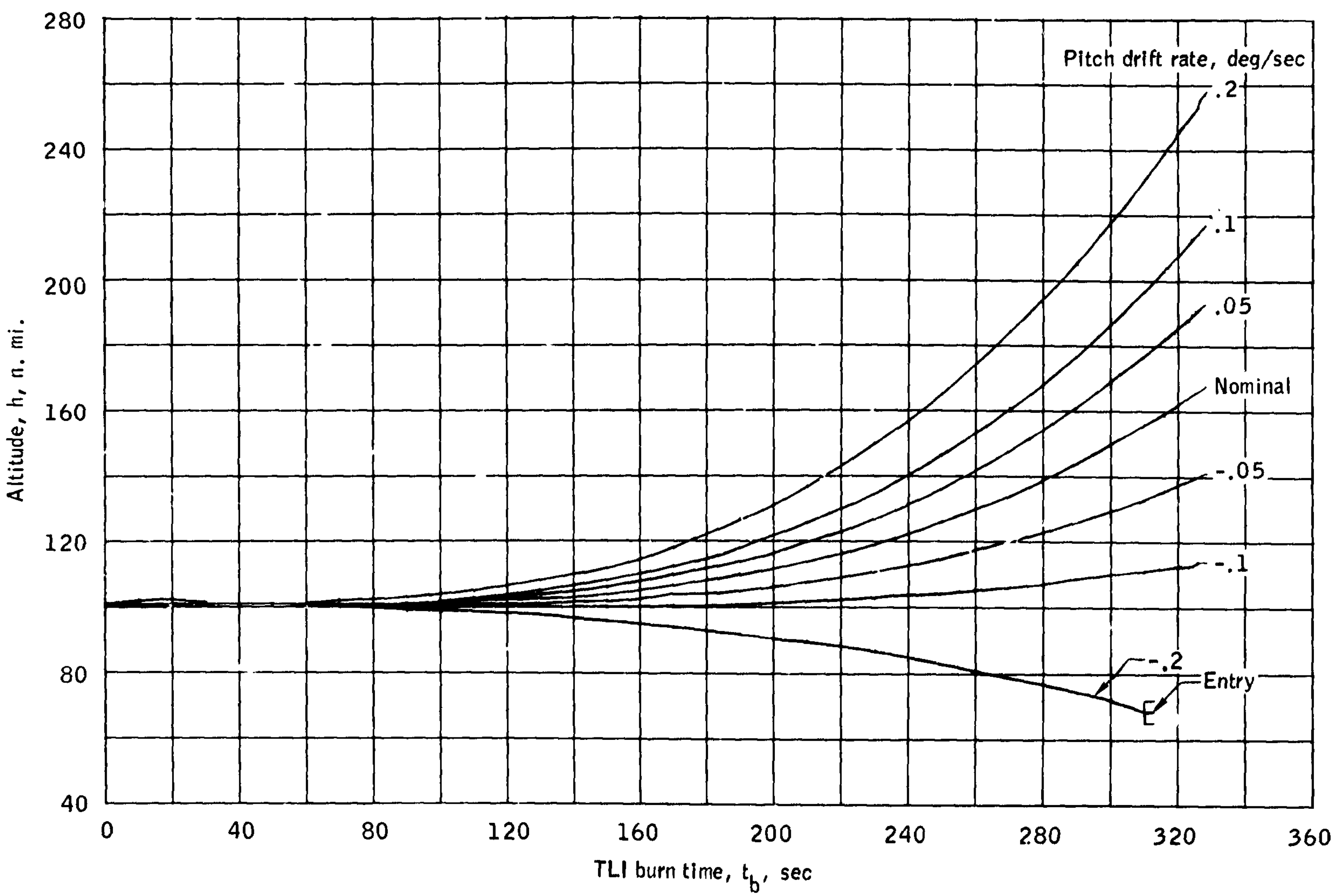


Figure 28.- Altitude time histories for various pitch drift rates.

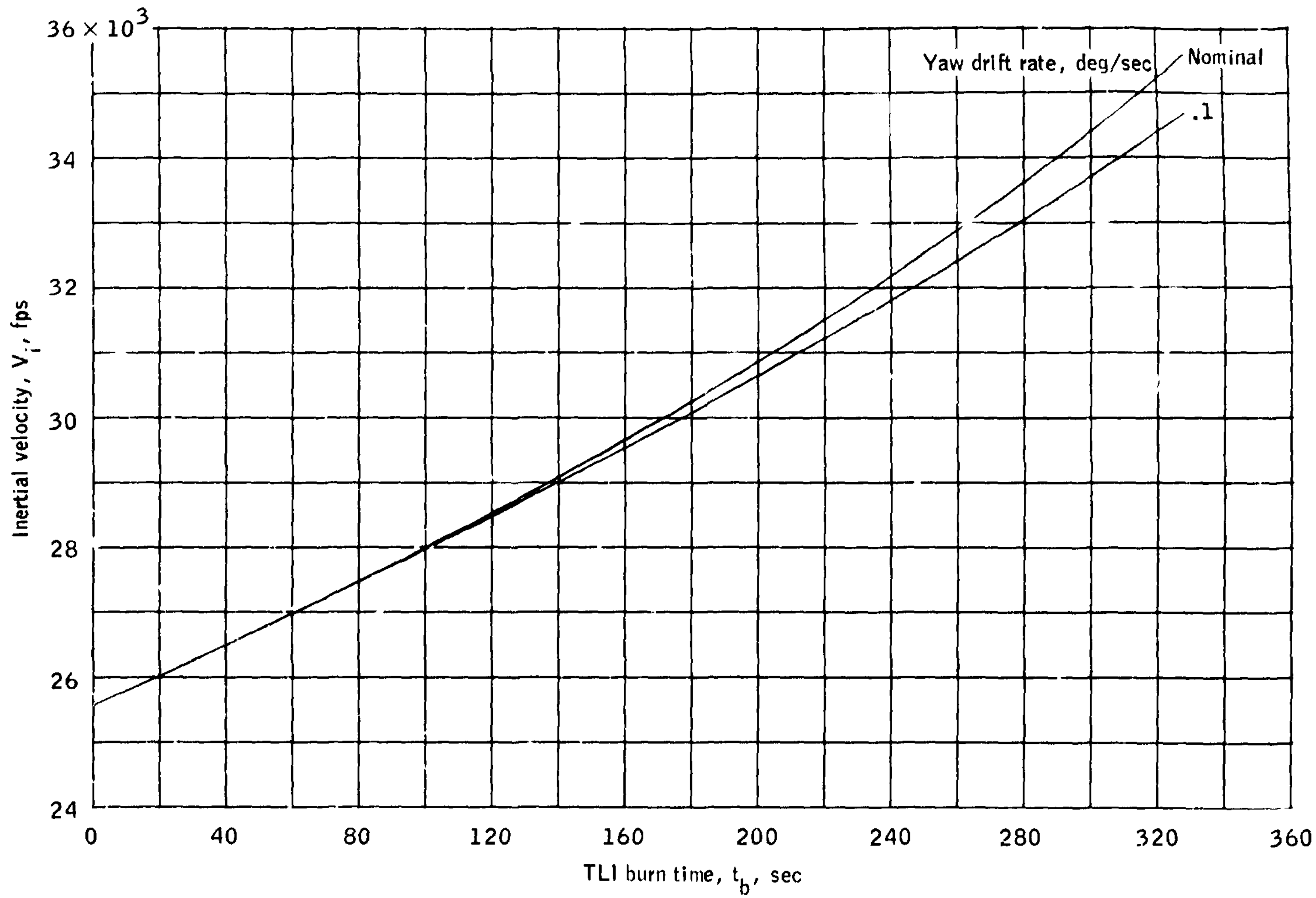


Figure 29.- Inertial velocity time histories for yaw drift rates of 0 and .1 degree per second.

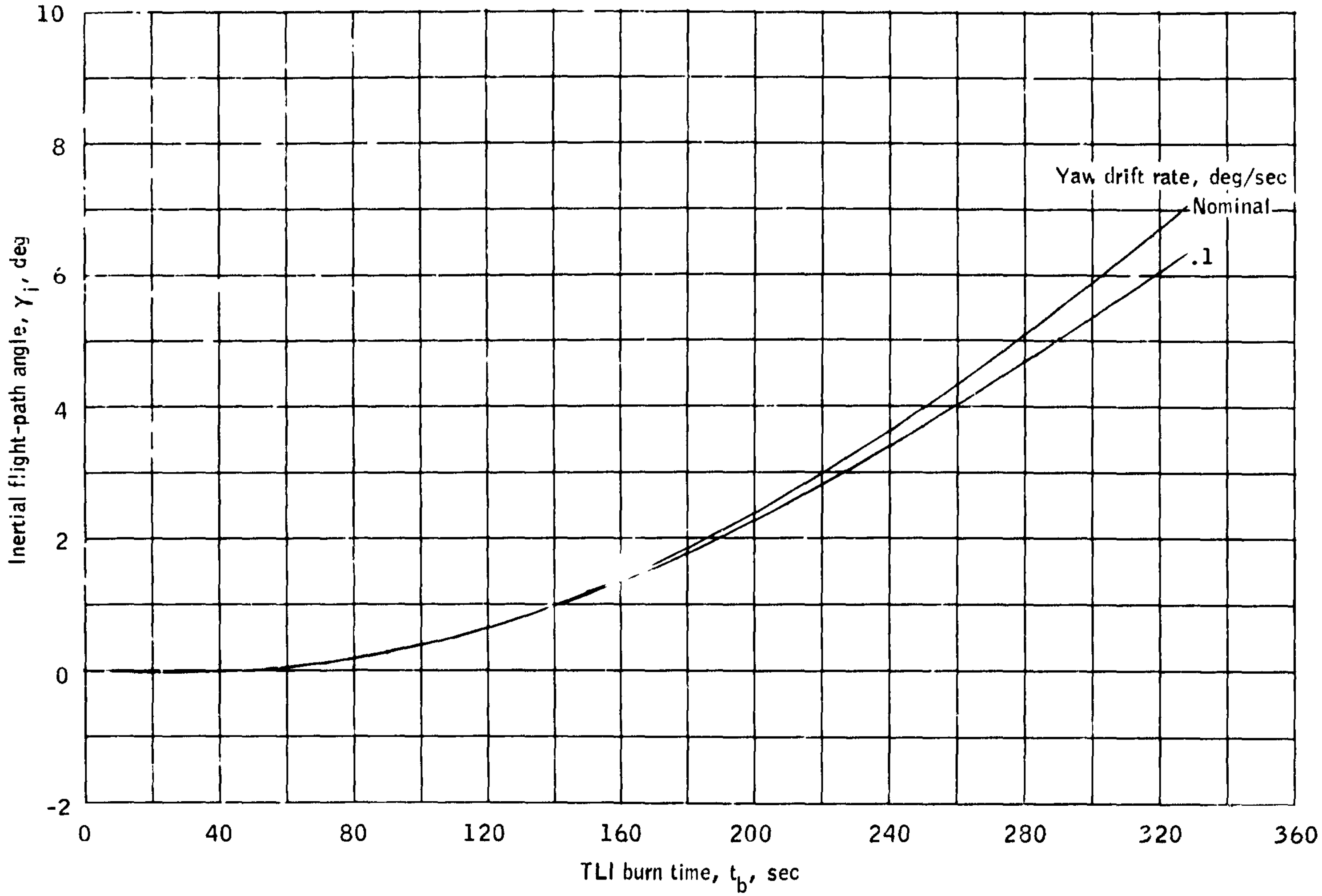


Figure 30.- Inertial flight-path angle time histories for yaw drift rates of 0 and .1 degree per second.

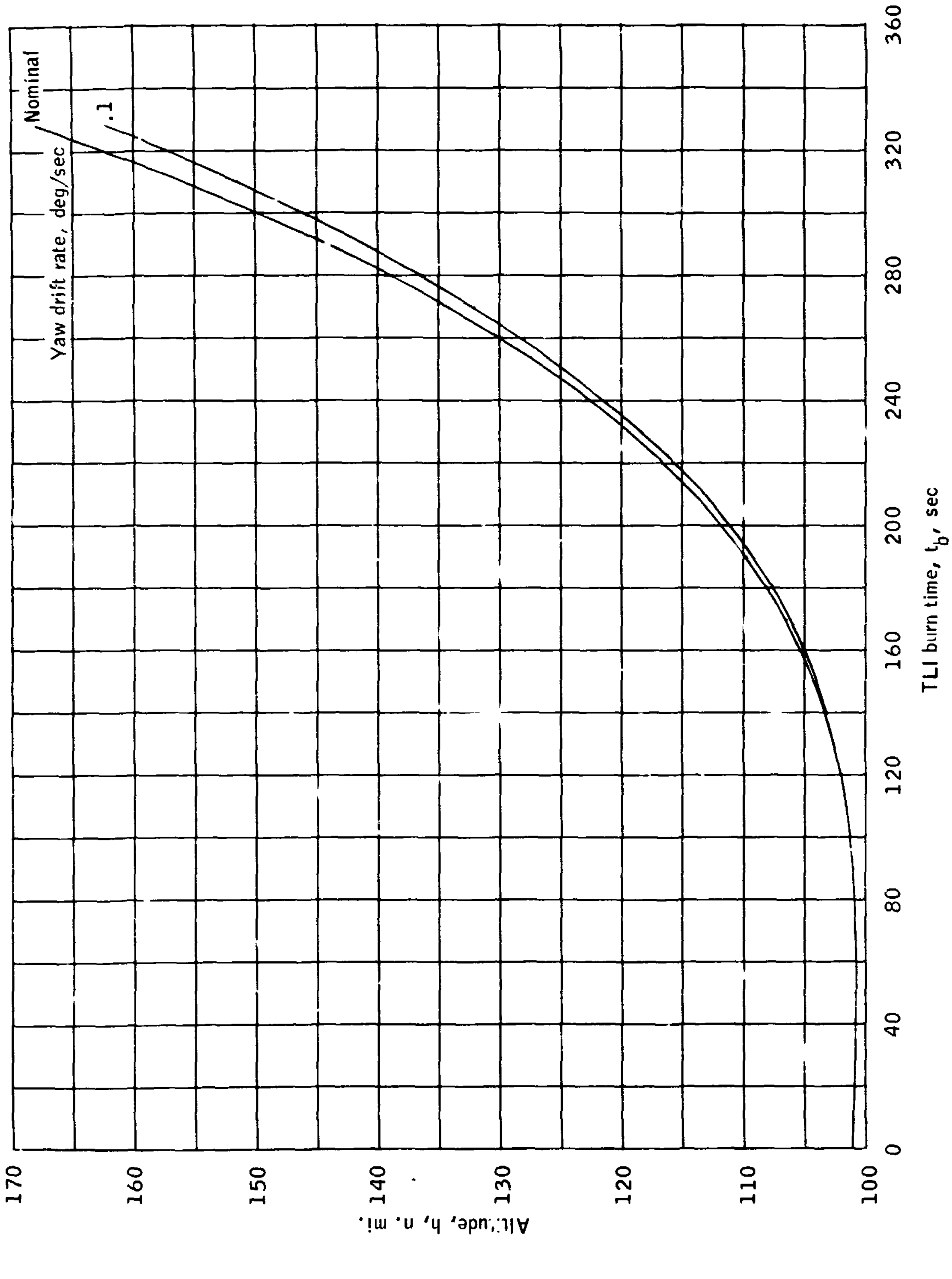


Figure 31.- Altitude time histories for yaw drift rates of 0 and .1 degree per second.

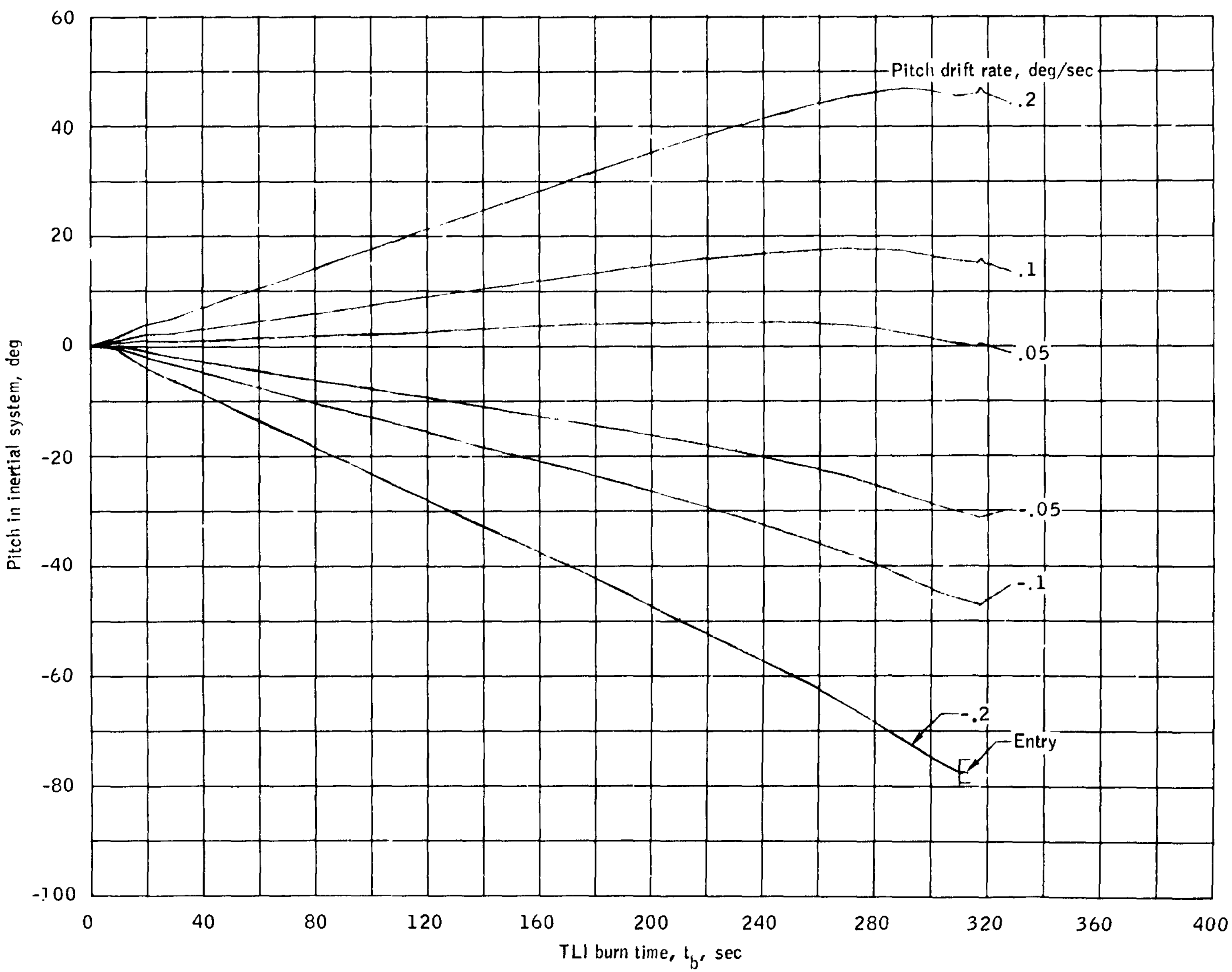


Figure 32.- Pitch attitude time histories in inertial system for various pitch drift rates.

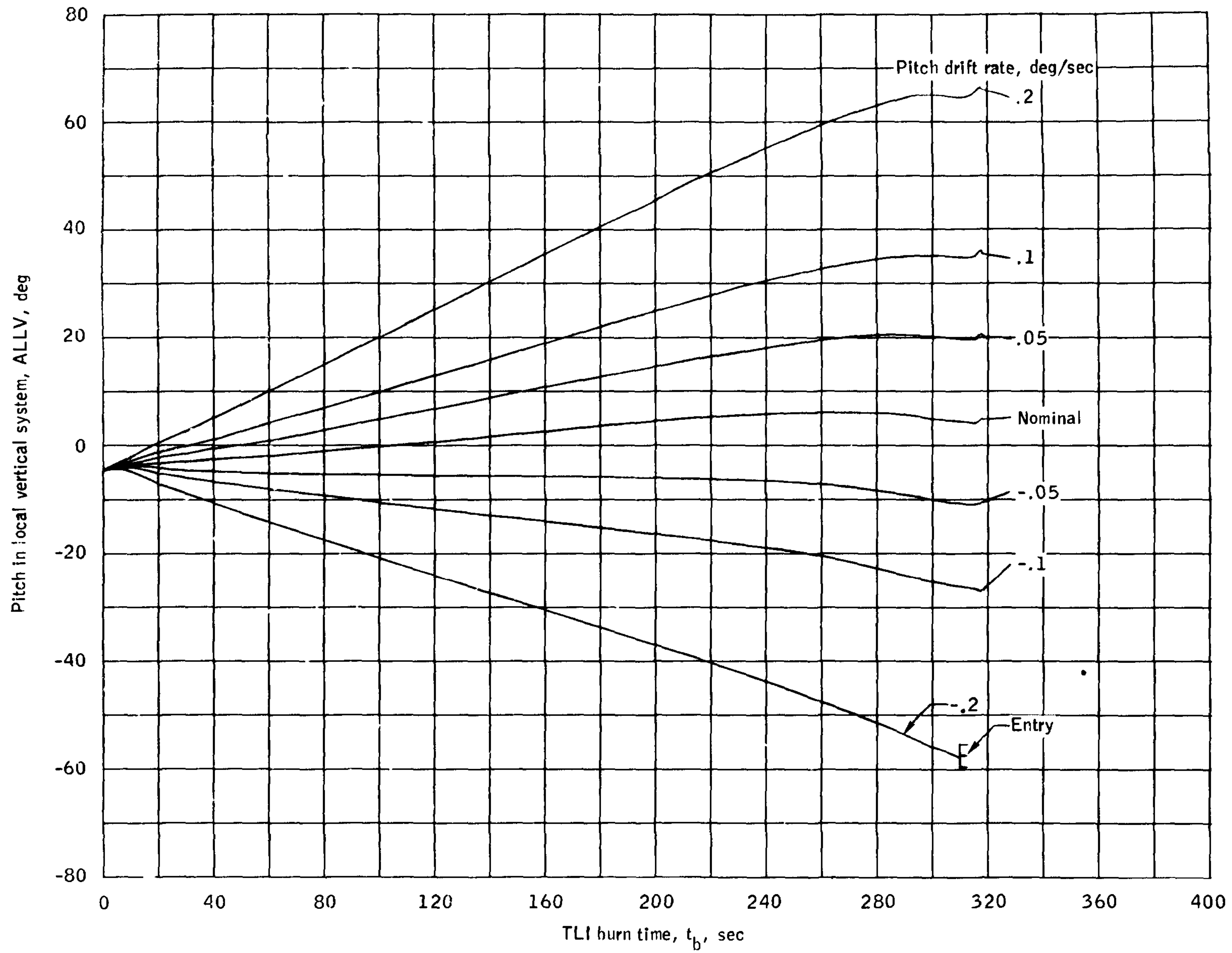


Figure 33.- Pitch attitude time histories in local vertical system for various pitch drift rates.

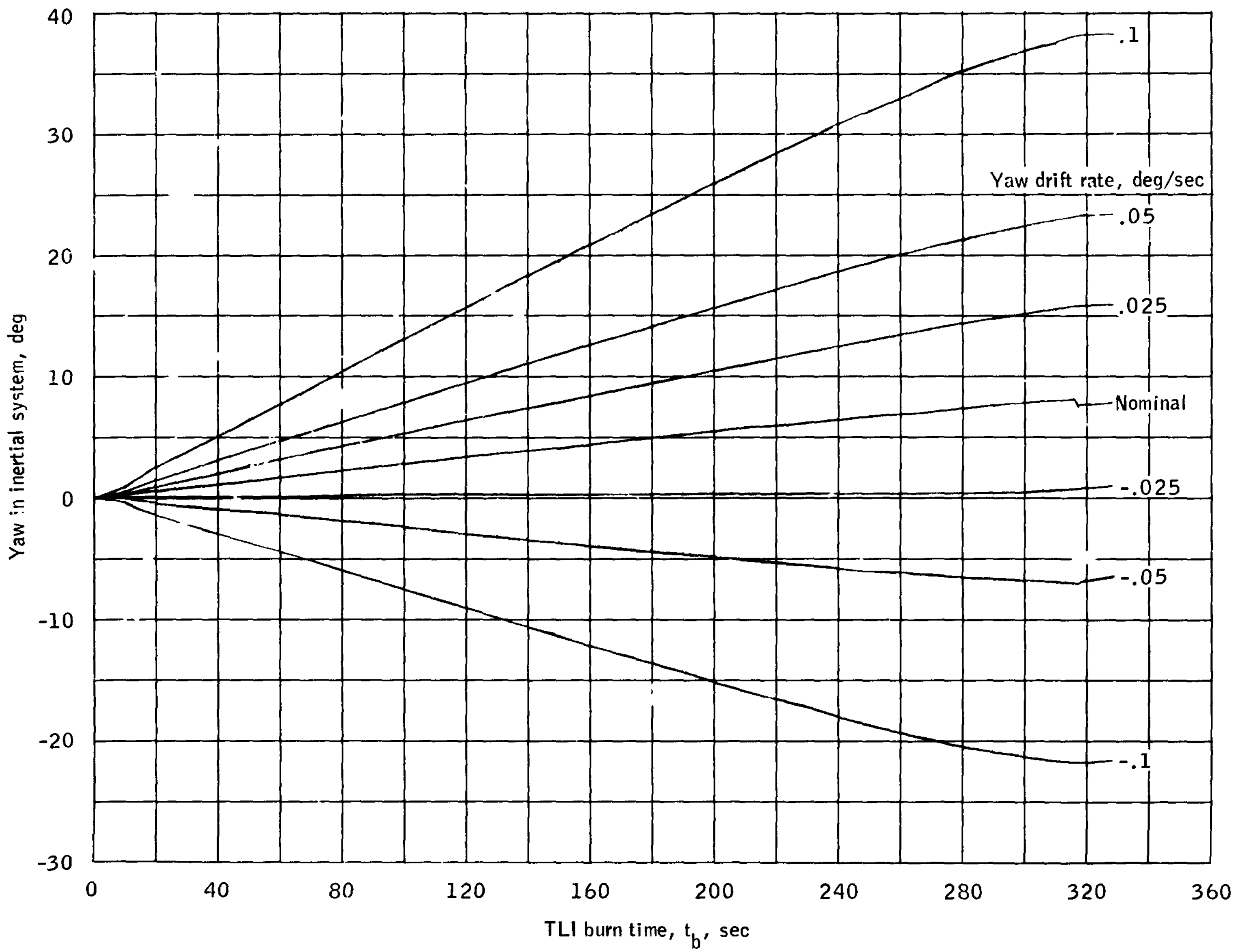


Figure 34.- Yaw attitude time histories in inertial system for various yaw drift rates.

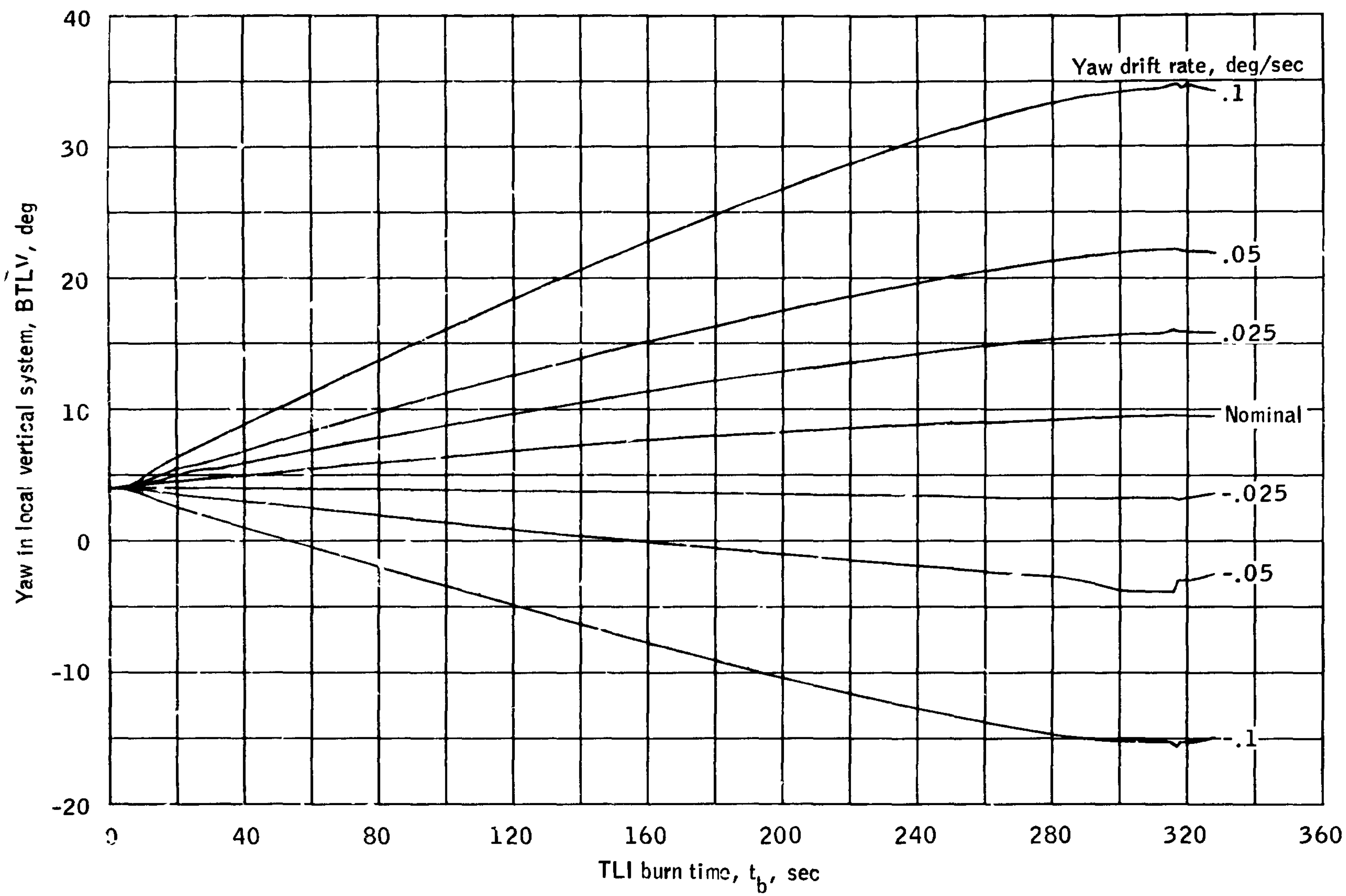


Figure 35.- Yaw attitude time histories in local vertical system for various drift rates.

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